CRACKING IN CEMENT TREATED BASES

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SUMMARY

The object of this research was to find the cause or causes of the cracking that commonly occurs during the curing period of soil-cement bases.

Based on theory and experience, a number of causes were postulated: expansive clay, moisture and cement contents, and temperature differential existing in the soil-cement mixture. In order to prove or disprove these assumptions, two distinct tests were devised.

Test No. I was designed to discover whether a relationship existed between clay content, moisture and cement contents, and cracking. The procedure was to hold one content constant and vary the remaining contents in sequence. This method proceeded in a manner similar to iteration.

Test No. II was designed to discover whether a relationship existed between temperature variation and cracking during the early curing period. This test utilized specimens similar to those used in Test No. I which were subjected to a 70 deg. F. temperature differential across the six-inch deep specimen, i.e., the upper surface was held at 140 deg. F. while the bottom was held at 70 deg. F.

In order to facilitate the testing procedures, two testing apparatuses were devised, an automatic compactor which molded a rectangular specimen and a temperature differential box which induced a temperature differential in the specimen.

Pilot studies were performed on curing methods, "speedy" moisture determinations, water retention and autogenous shrinkage of Type I Port-

land cement and volume change characteristics of the four different soils to be used in the tests.

Some of the more significant results were the discovery that cement content is not a single factor in producing cracking, and that temperature differential existing in the base helped accelerate cracking. Other results showed the type soil, either friable or clayey, with a variance of the moisture content, above or below optimum, could be either beneficial or detrimental to the durability and cracking of the soil-cement mixtures. It was also found that certain type soils are more susceptible to cracking than others and thereby recommended that prescribed tests be performed on potential soils to be used in soil-cement construction.

CHAPTER I

INTRODUCTION

General

One result of the demand for economical road construction is soil stabilization. Mechanical soil stabilization as applied to road building is the proper combination or adjustment of soil fines with the coarse material to produce a mixture using local materials that will be stable under adverse weather and traffic conditions.[1*] Through research and experiments, certain additives have proven economical and advantageous to the soil structure itself. Some of the additives more commonly used are calcium chloride which acts as a soil flocculant, fly ash which produces a pozzolanic reaction in some soils, Portland cement which results in a strong cementing action, and liquid asphalt which is a good waterproofing agent as well as a cementing agent for the soil. The most commonly used is Portland cement, producing a mixture better known as soil-cement.[2]

Concurrently with the development of soil-cement bases, economical and technical problems developed. The major technical problem is the development of large shrinkage cracks during the hardening process. These cracks cause weak planes in the base which permit water to enter more readily into the subgrade, thereby weakening the total structure. A solution, to a great extent, has been in reducing the cement-content

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* Refer to Bibliography for numbers.

from 10 to 12 per cent so as to have present in the soil only 3 to 4 per cent cement content.[3] The resulting cement-treated base is weaker and develops more shrinkage cracks at closer intervals, but the individual cracks are smaller and can be corrected effectively with a liquid asphalt coat prior to placement of the surface course. This correction is also a tremendous help economically.

Shrinkage cracks are probably caused by other factors than cement content ratio, as for instance by the amount of expansive clay present in the soil and by improper curing. Shrinkage increases with increasing expansive clay content of the soil. A majority of these cracks extend into the soil-cement only one to three inches with full width being five feet or more apart.[4] These cracks can be appreciably reduced by replacing a portion of the Portland cement with flyash. From this addition however, there would be a definite decrease in strength, depending on soil texture.[2] Soil texture has a definite effect on the benefits of using flyash as an additive in soil-cement. There is a compressive strength loss in plastic loess (41.8 per cent 5 micron clay) and alluvial clay (74.3 per cent 5 micron clay) but a reduction in shrinkage cracking. The best strength gains due to pozzolanic reaction, from which flyash derives its strength, appear in sands, due probably to its low clay content.[2]

It can be concluded from the above statements that if there existed in the soil-cement a high sand content and low clay content, there would not exist sufficient justification for the addition of flyash for shrinkage reduction purposes. Sufficient justification would exist however, for the using of flyash for economical reduction of the cement content.

The type of soil is the most important single factor affecting the quality of soil-cement. If the soil is unsuitable, e.g., a very fat clay or highly organic, little can be done at the present time to make the resulting soil-cement satisfactory economically. In general, experience has shown that soils meeting the following conditions can be hardened effectively through the addition of reasonable amounts of cement:[5, 6]

Per cent finer than 0.002 mm less than 35 per cent

Per cent passing No. 4 sieve (4.76 mm) greater than 55 per cent

Maximum size not greater than 3 inches

Liquid limit less than 50 per cent

Plasticity index less than 25 per cent

Although the Portland Cement Association[8] has found that soils of the same texture, horizon, and series require the same cement treatment, investigations by Maclean[5] have indicated that the nature of the action associated with the clay, as well as the type of clay mineral, influences the response of a soil to cement stabilization. He found that calcium clays were the most easily stabilized, whereas sodium and hydrogen clays were more difficult. The addition of hydrated lime to sodium and hydrogen clays in order to convert them to the calcium form has resulted in satisfactory soil-cement. Experience has shown that soils composed of the non-expansive clay minerals are more suitable for cement stabilization than soils composed of the expanding lattice-type minerals, such as kaolinite. Thus a knowledge of pedological soil classification systems and mineralogy is helpful when considering soil-cement stabilization.

A detailed study of the effect of organic matter on soil-cement was undertaken by Clare and Sherwood.[9] They found that organic compounds with high molecular weights, such as cellulose, starch, and lignin, did not effect strength, while those of lower molecular weights, such as nucleic acid and dextrose, acted as hydration retarders and resulted in lower strengths.[10]

Improper curing is a problem created largely by negligence. If the design water content is not properly retained after placement, improper hydration results. Numerous methods of curing have been proven effective.

Although the large shrinkage cracks can be controlled to a great extent the direct effects from the smaller cracks and weakened base on the subgrade have not been determined. The effects of the surface cracks have been determined to some extent.

Actual experiments have shown that when the soil-cement cracks after the bituminous surface has been placed, the effects on the surface are small and will most probably be sealed by the traffic. Also, if cracks occur before the placement of the bituminous surface, which is normally the case, the bituminous mix itself will fill and seal the cracks.[4] The sealing of these cracks has a tremendous influence on the service life of the soil-cement because sealing prevents water infiltration. Water permitted to filter down along the cracks will not materially weaken the soil-cement itself; however, if the cracks protrude completely through the soil-cement base then water will be able to filter to the subgrade and consequently may dampen and weaken it.[11]

Scope of Experiment

The objective of this research is to determine how certain factors affect cracking in soil-cement with emphasis being placed on cracking that occurs at an early age (during the curing period).

For the purpose of experimentation, some assumptions were made. The first assumption was that most cracking in soil-cement mixture can be attributed to the clay that is present in the soils, that is if the clay is an expansive clay, then the resulting mixture will retain some of the clay's expansive characteristics. Other assumptions were that moisture content, cement content, and temperature differential (temperature gradient in the base) were factors in cracking.

Based on these assumptions, two different tests were devised. These tests were designated as Test No. I and Test No. II. Test No. I was designed to find if a relationship existed between clay, moisture content and cement content, and cracking. Test No. II was designed to find if a relationship existed between temperature differential and cracking.

CHAPTER II

DESCRIPTION OF MATERIALS AND TESTING EQUIPMENT

Soils

Four different soils were used in this experiment and designated as Soil A, Soil B, Soil C, and Soil D. All of these soils were residual and obtained from the B horizon except Soil D, which was obtained from the A horizon.

Soil A, a well-graded, dark red, sandy loam soil, was obtained from Bartow County. Soil A was used in the cement stabilized base on U. S. 411 between Rome and Cartersville, Georgia.

Soil B, a well-graded, brownish yellow, sandy clay loam soil, was also obtained from Bartow County. This soil was used as the sub-base for the above-mentioned project.

Soil C, a well-graded, light red sand loam soil was obtained from Fulton County.

Soil D is a well-graded, brownish gray, sandy loam soil obtained from Douglas County. This soil is a favorite soil used in soil-cement bound macadam in the State of Georgia.

Physical Tests

After securing the soils, only those portions passing a No. 4 United States Standard Sieve were placed in containers for use in the experiment.

The following standard tests were performed on each of the four soils for identification and classification:

1. Grain size analysis as specified in AASHO Designation T 88-57.
2. Plastic limit as specified in AASHO Designation T 90-56.
3. Liquid limit as specified in AASHO Designation T 89-60.
4. Specific gravity as specified by AASHO Designation T 180-57.
5. Volume change as specified by G.H.D. - 800.09.

Tabular results of these physical tests are given in Table 1.

Admixtures

The only admixture used in this experiment was Type I Portland cement. The chemical composition of this admixture is given in Table 2.

Testing Equipment

Mixing Equipment

The soil, cement, and water needed for the 6 in. x 6 in. x 18 in. specimens were blended with a Read Standard Grant mixer equipped with a hook blade. The mixture was blended at a speed of 125 revolutions per minute. Mixer is shown in Fig. 1.

The mixture needed for moisture density specimens was blended with a Hobart C-100 mixer equipped with a flat blade. Mixer speed was 144 revolutions per minute.

Compaction Equipment

The 6 in. x 6 in. x 18 in. specimens were compacted with a modified Rainhart mechanical compactor equipped with an 11 pound 1 in. x 5-7/8 in. rectangular-faced hammer.

This compactor was calibrated to the Standard Proctor. The number of blows required per layer was first computed from energy

Table 1. Properties of Soils

Specimen No.	A	B	C	D
% Passing U. S. Standard Sieve No.				
4	100.0	100.0	100.0	100.0
10	99.6	85.2	99.0	95.8
40	88.2	60.8	83.0	62.6
60	72.1	51.6	74.0	52.4
100	45.2	43.2	62.0	42.5
200	36.7	41.4	52.0	36.7
% Sand	70	62	59	69
% Silt	24	14	25	16
Clay	6	24	16	15
Liquid Limit	20.7	23.0	27.0	14.7
Plastic Limit	18.0	14.2	11.0	13.5
Plasticity Index	2.7	8.8	16.0	1.2
Specific Gravity	2.71	2.76	2.71	2.67
% Volume Change Ga. Hwy. Dept. Art. 800.09	3.5	7.3	12.9	1.7
Ga. Hwy. Dept. Classification	A-1 Subgrade	C Subgrade	11B[1] Embankment	1-A Embankment
AASHO Classification	A-4(0)	A-4(1)	A-6(6)	A-4(0)
Location (Ga. County)	Bartow	Bartow	Fulton	Douglas

Table 2. Portland Cement Analysis

Chemical Composition, %	
Silicon dioxide, SiO_2	20.46
Ferric oxide, Fe_2O_3	2.44
Aluminum oxide, Al_2O_3	5.90
Sulphur trioxide, SO_3	2.08
Calcium oxide, CaO	62.87
Magnesium oxide, MgO	4.18
Insoluble residue	0.30
Loss on ignition	1.38
Specific surface area, Blaine (sq. cm/gm)	3464

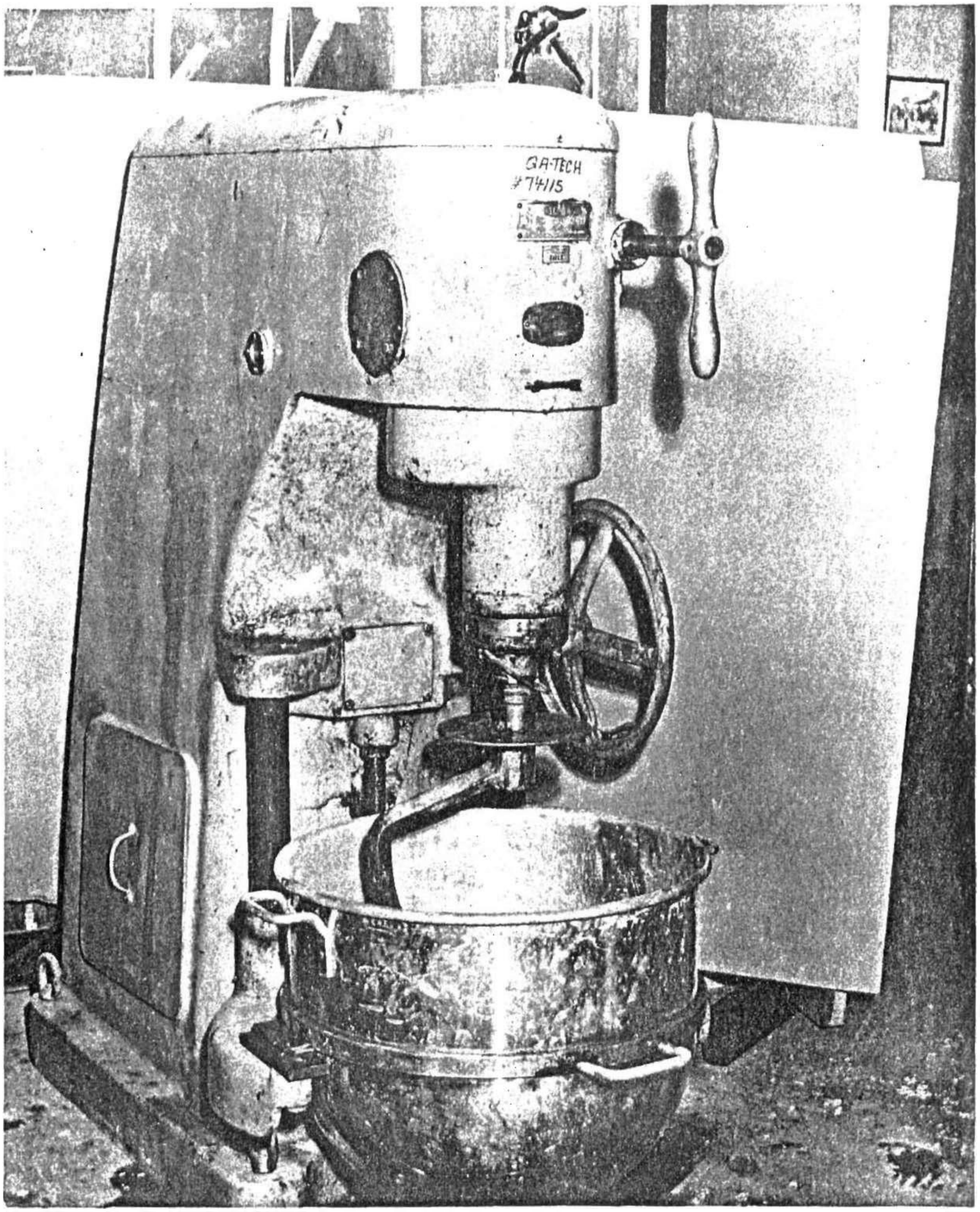

Figure 1. Read Standard Grant Mixer.

equations with the resultant number being 125 blows. After compacting several specimens, it was found that 123 blows per layer produced the same densities as the standard Proctor energy. The soil used for this calibration was Soil D. Each of three 2 in. layers of the specimen received 123 blows from a height of 12 in. above the surface of the soil. This compactor is shown in Fig. 2. A detailed drawing of the mold is presented in Fig. 3.

The moisture density samples were compacted with equipment as required for Standard Proctor compactor test, AASHO Designation T-99-57.

Temperature Differential Equipment

Samples to be subjected to a temperature differential were placed in the apparatus, shown in Figs. 4 and 5. Eight 250 watt bulbs maintained the top half of the sample at 140 deg. F., while water circulating through sheet metal forms maintained the lower half at approximately 70 deg. F.

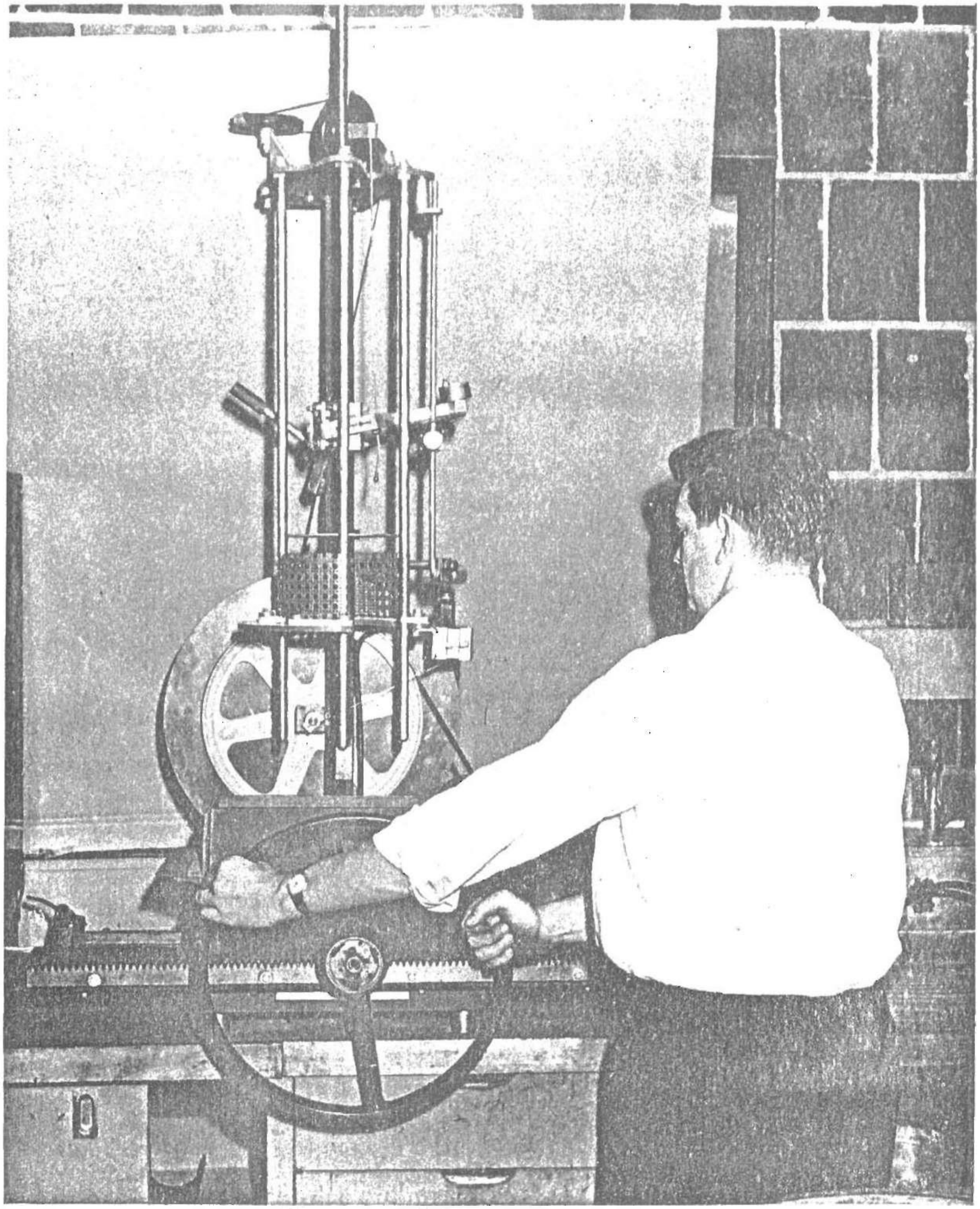

Figure 2. Modified Rainhart Mechanical Compactor.

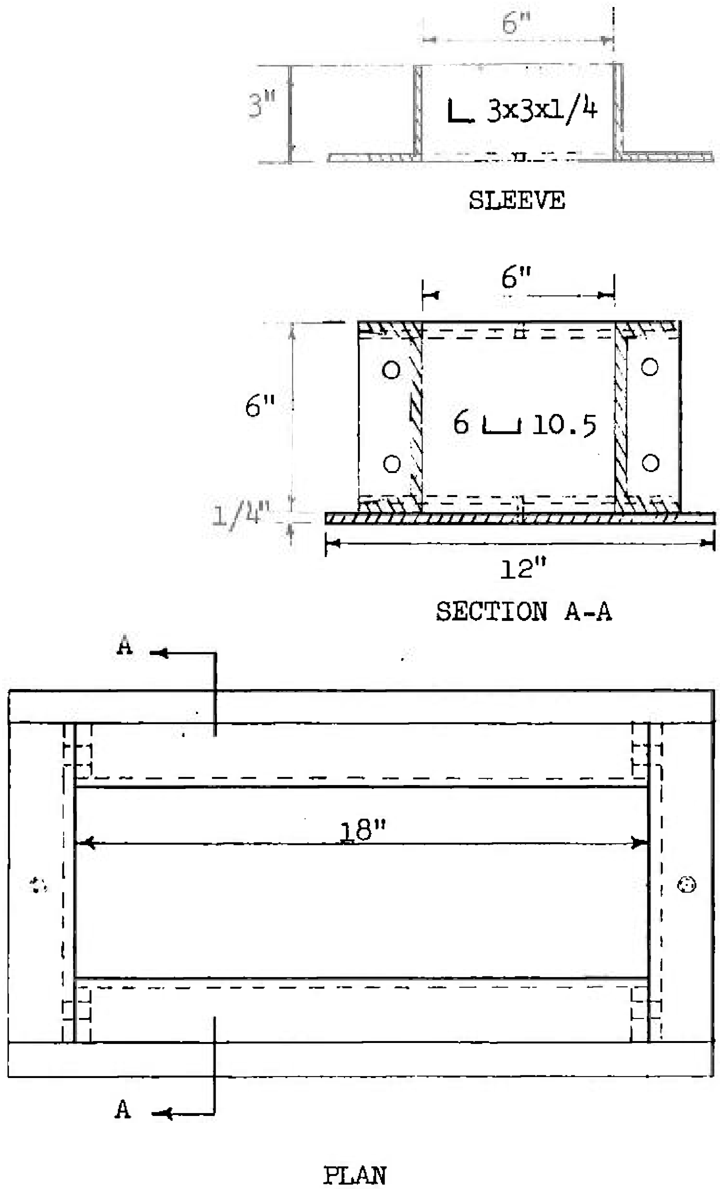

Figure 3. Test Specimen Mold.

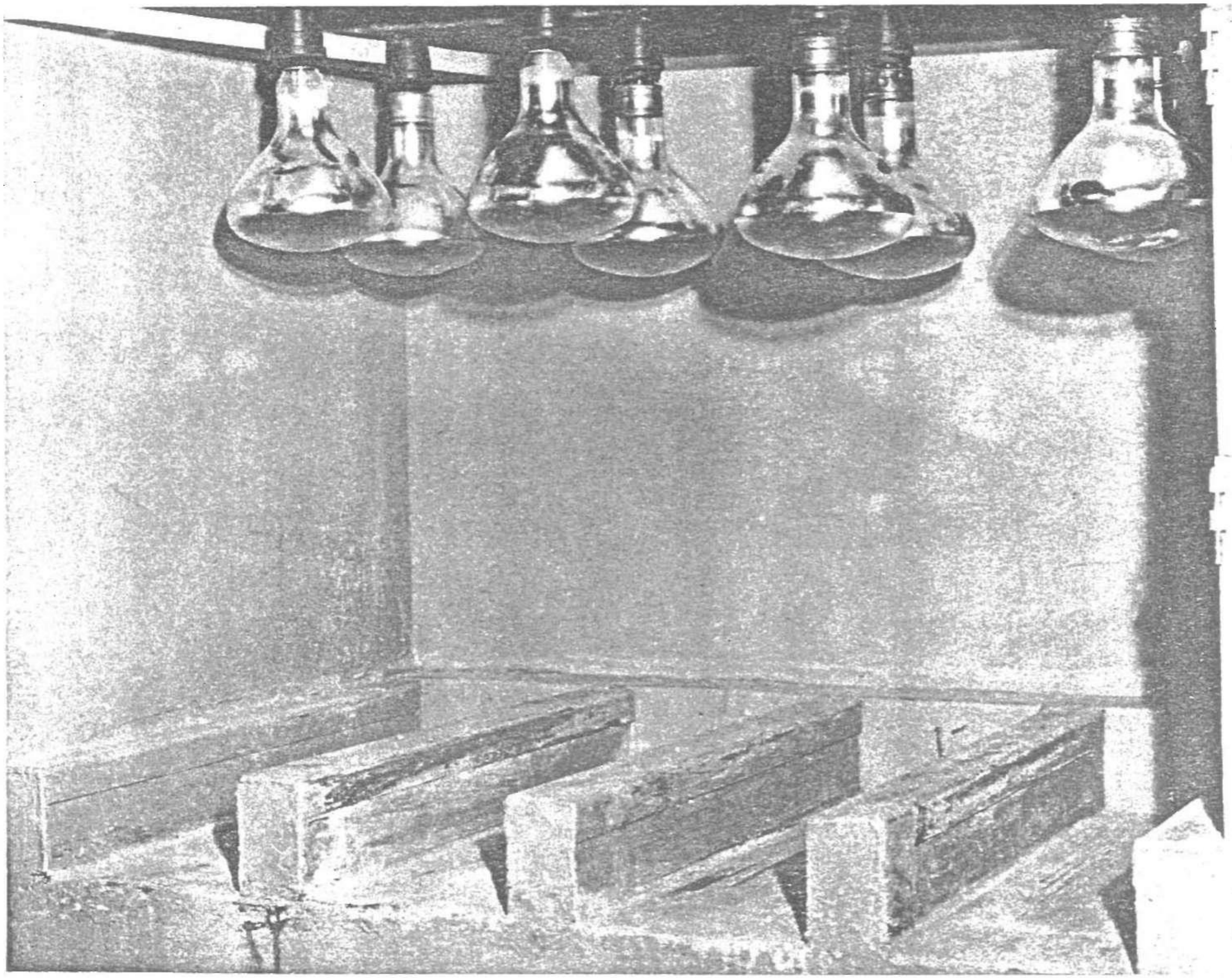

Figure 4. Temperature Differential Apparatus.

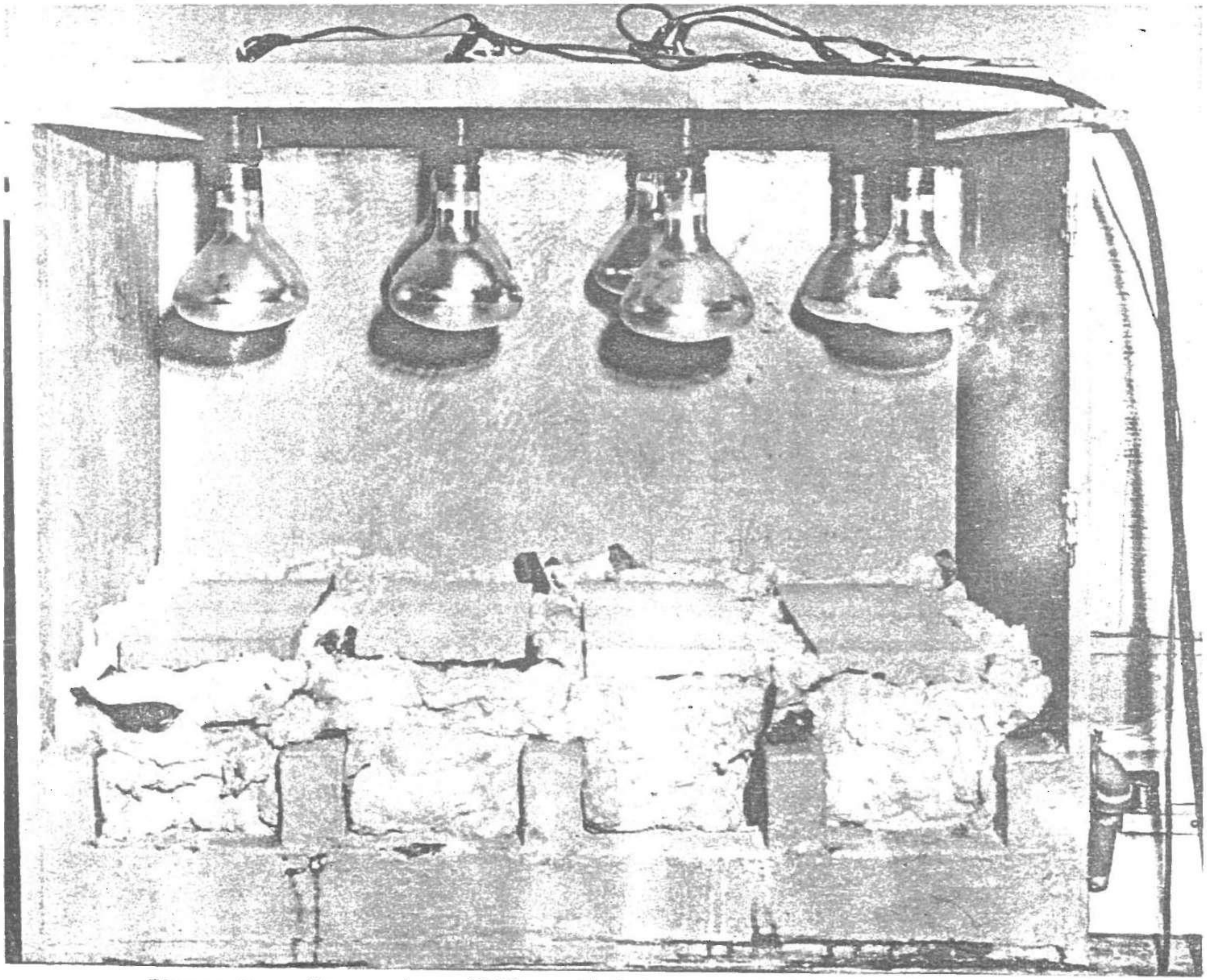

Figure 5. Temperature Differential Apparatus with Test Specimens.

CHAPTER III

PILOT STUDIES

Water Retention and Autogenous Shrinkage Properties of Type I Portland Cement

A thorough study was made on the water retention properties and autogenous weight change in the paste of Type I Portland cement. Autogenous weight change is the loss of weight in a Portland cement paste during the hydration due to the chemical reaction heat loss. This study was performed in the following manner:

1. Hold the cement constant at 200 grams and vary the water from 50 grams in increments of 10 grams to 200 grams, a total of 15 different combinations being obtained.

2. Vigorously mix each sample 90 seconds, then after mixing,

3. Seal the container to prevent any water from evaporating.

4. Allow to cure at constant temperature.

5. Weigh each sample at 7, 28, and 60 days and record weights.

6. After a 60-day curing period, remove seals, place in oven at 110 deg. C. for a period of seven days and record final weights.

It was found that the autogenous weight change during the 60-day period was equal to above 0.25 per cent of the weight of the cement. These values are shown in Table 3. An interesting point to note here is that there was not any significant difference in weight loss between the different water cement-ratios.

Table 3. Water Retention Properties of Type I Portland Cement

Can No.	Initial Wt. of Cement $+H_2O$	Water-Cement RATIO-(W/C)	Per Cent Wt. Loss After 60 Day Cure	Total Wt. of Water Retained After Entire Test (gm)	Percent Water Retained After Entire Test (gm)
1	250	0.25	0.40	23.5	47.0
2	260	0.30	0.38	27.6	46.0
3	270	0.35	0.26	30.2	43.1
4	280	0.40	0.29	32.9	41.1
5	290	0.45	0.34	33.1	36.8
6	300	0.50	0.23	34.7	34.7
7	310	0.55	0.26	34.9	31.7
8	320	0.60	0.25	35.4	29.5
9	330	0.65	0.24	37.0	28.5
10	340	0.70	0.24	35.7	25.5
11	350	0.75	0.20	34.6	23.1
12	360	0.80	0.30	36.6	22.9
13	370	0.85	0.24	36.7	21.6
14	380	0.90	0.21	36.1	20.1
15	390	0.95	0.15	36.5	19.2
16	400	1.00	0.25	36.3	18.2

In determining the water retention properties of the Type I Portland cement, it was found that the low water-cement ratios retained little water, but as the water-cement ratio increased the water retention also increased. This increase in water retention continued until the water-cement ratio was about 0.5. At this point the water retention, which was about 36 grams, remained constant for the remaining larger water-cement ratios. These values are given in Table 3 and graphs plotted from these values are shown in Figs. 6 and 7.

Volume Change

A study was made of Type I Portland cement, Soil A, Soil B, Soil C, and Soil D volume change characteristics due to the loss of evaporable water from the specimens. This volume change was determined by the Georgia State Highway volume change method No. 800.09. This method entailed making two identical specimens of each soil, placing one specimen in a water bath and the other in an oven at 110 deg. C. for a 24-hour period. After this time interval the total volume difference between the respective specimens was recorded as per cent volume change with respect to the initial volume, e.g., difference between swell and shrinkage at zero load.

Due to the small size of the specimen used, the volume change recorded for the Type I cement was not significant. The volume changes recorded for the four soils are shown in Table 1 and the apparatus used for this test is shown in Fig. 8.

Correlation of the "Speedy" Moisture Determination Method

This study was made to determine the correlation of the "Speedy"

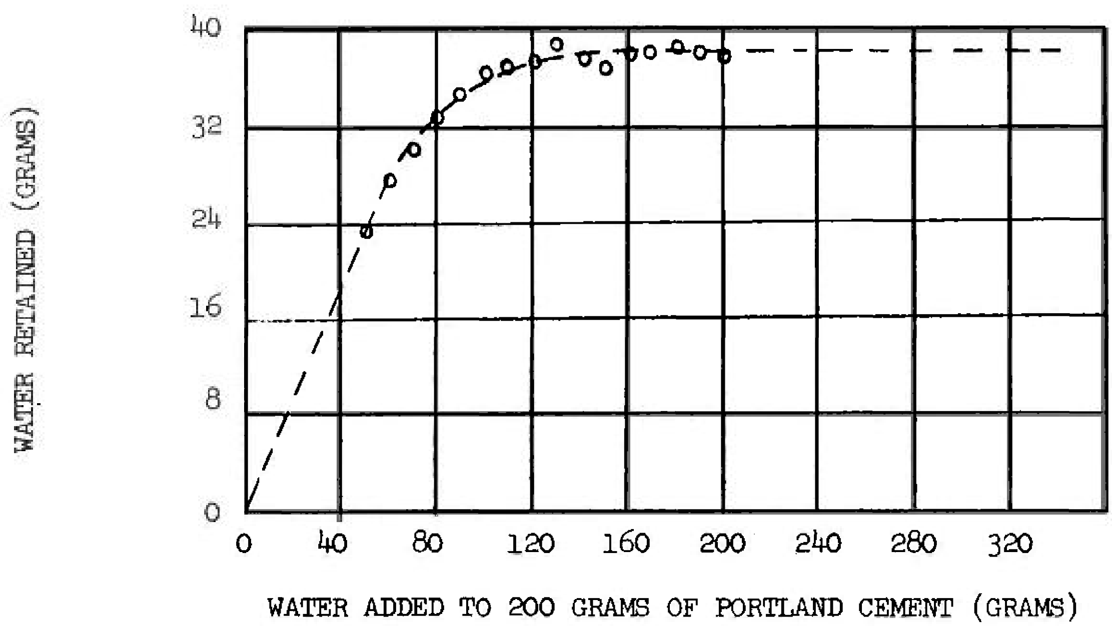

Figure 6. Water Retained Vs. Water Added to 200 Grams of Portland Cement.

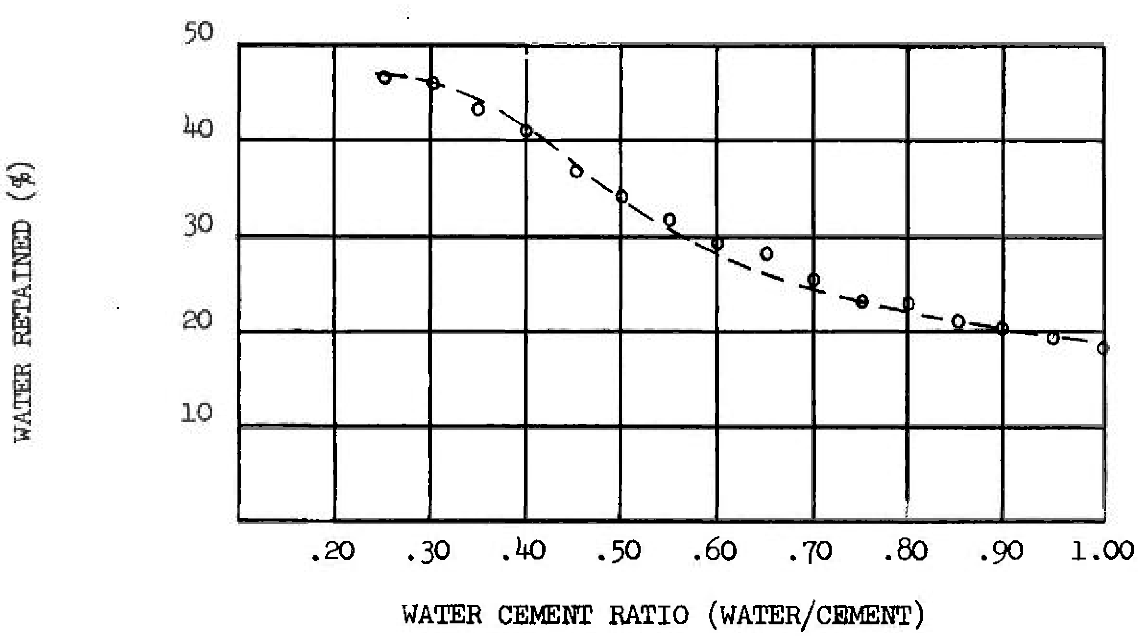

Figure 7. Per Cent Water Retained Vs. Water-Cement Ratio.

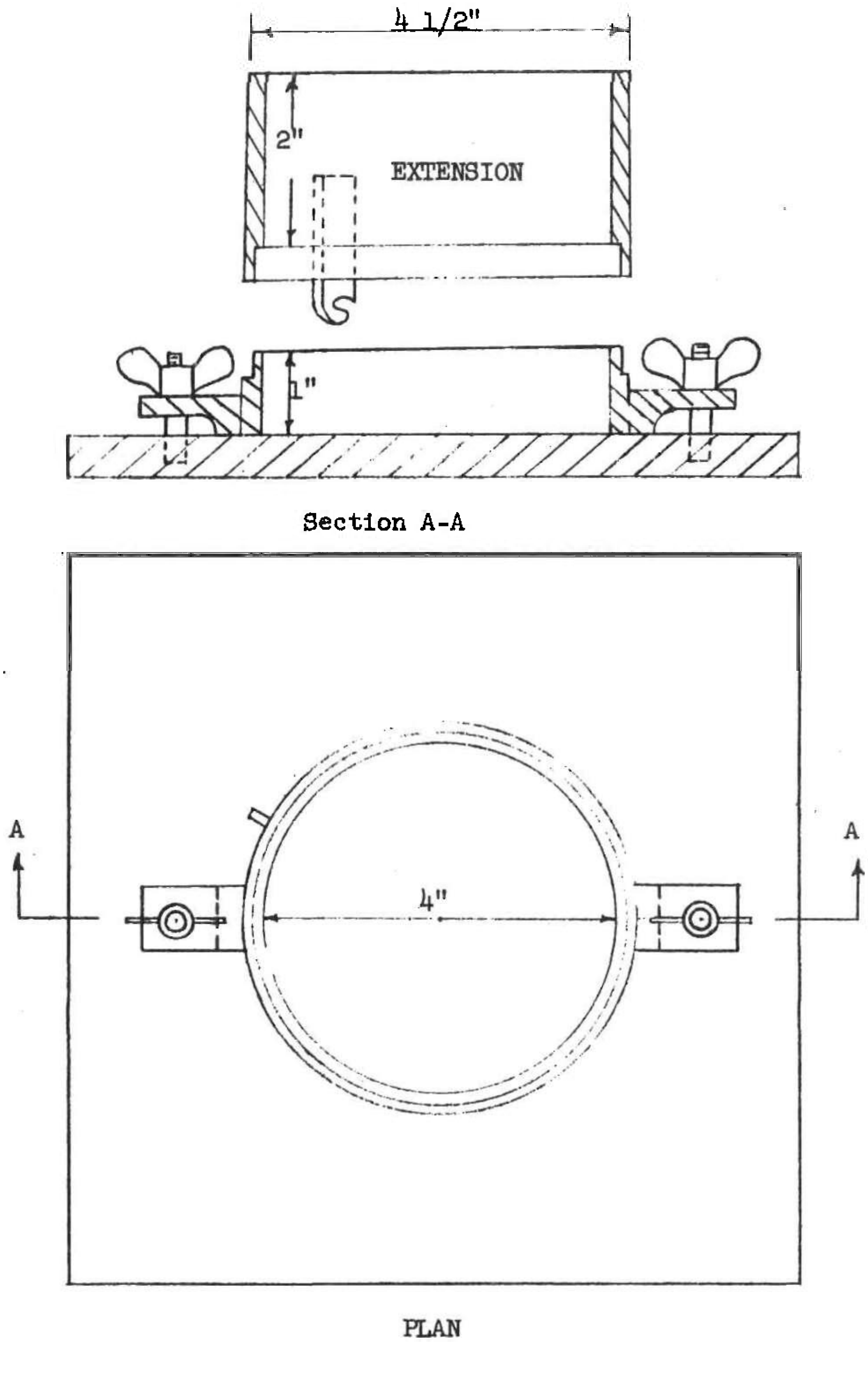

Figure 8. Volume Change Apparatus.

moisture tester, manufactured by the Alpha Lux Company, Inc., to the actual moisture content by the oven dry method, for the four soils used in this experiment. Calibration curves were plotted from this data in Table 4 and are shown in Figs. 9, 10, 11 and 12. This calibration permitted more accurate hydroscopic moisture determinations to be made for the undried soils prior to mixing, utilizing a small sample.

Specimen Size and Mold Make-Up

Specimen and mold size was rectangular shaped with dimensions of 6 in. x 6 in. x 18 in. The mold is constructed of 6 in. channel iron with a 3 in. x 3 in. angle iron being used for the sleeve. This mold is shown in Fig. 3.

Relationship of Optimum Moisture Content to Various Cement Contents

This study was made to determine what relationship the optimum moisture content would be for different soils with various cement contents, i.e., what effect the different cement contents would have on the optimum moisture and density of the soils. Moisture density relationships as designated by AASHO Method T99 were obtained on Soils A, B, C, and D and with each having an 11 and 22 per cent cement content. It was found that only one soil, Soil C, showed any significant change which was an increase in density of about 3½ lbs. The reason for this change is attributed to the light weight of Soil C. Results of this study are shown in Figs. 13 - 16.

Curing of Specimen

The objective of this study was to develop a curing process that

Table 4. "Speedy" Moisture Determination Correlation With Soils A, B, C and D

Soil "A"		Soil "B"		Soil "C"		Soil "D"	
"Speedy"	Actual	"Speedy"	Actual	"Speedy"	Actual	"Speedy"	Actual
0.8	1.3	0.6	1.0	6.2	7.2	6.0	6.6
0.8	1.4	0.8	1.0	5.5	6.5	6.8	7.0
0.8	1.3	0.6	1.0	5.8	6.8	7.6	7.8
3.0	4.0	0.6	1.1	6.0	6.5	8.2	8.1
4.1	5.1	0.6	1.1	4.8	5.8	6.0	6.6
1.2	1.7	1.0	1.4	4.9	5.7	1.3	1.8
4.5	5.2	1.0	1.4	4.8	6.4	1.8	2.2
5.3	6.1	1.0	1.5	13.2	13.3	7.4	7.8
5.5	5.9	3.2	4.0	13.3	13.7	2.1	2.7
3.3	4.1	3.2	3.9	14.0	14.9	8.0	7.8
4.0	4.5	2.5	3.4	12.0	13.3	2.0	2.7
4.8	5.3	2.1	3.0	13.5	14.0	6.2	6.6
6.0	6.4	1.4	2.0	14.1	15.6	7.5	7.5
7.1	7.1	1.0	1.4	15.6	15.8	1.5	1.8
6.5	7.2	0.7	1.0	15.0	16.0	7.4	8.1
		0.7	0.8	15.4	16.5	2.0	2.0
		0.7	0.8	6.4	7.4	7.7	8.6
		0.7	0.8	6.4	7.4	7.7	8.6
				6.1	7.1	1.8	2.1
				6.2	6.9	5.5	6.6
						1.5	1.7

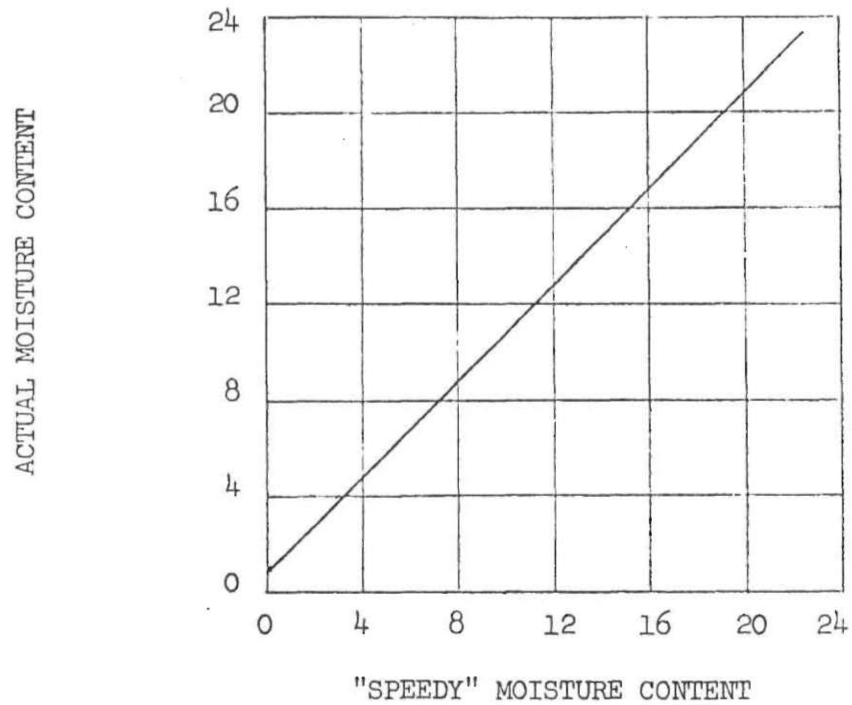

Fig. 9. "Speedy" Calibration for Soil A

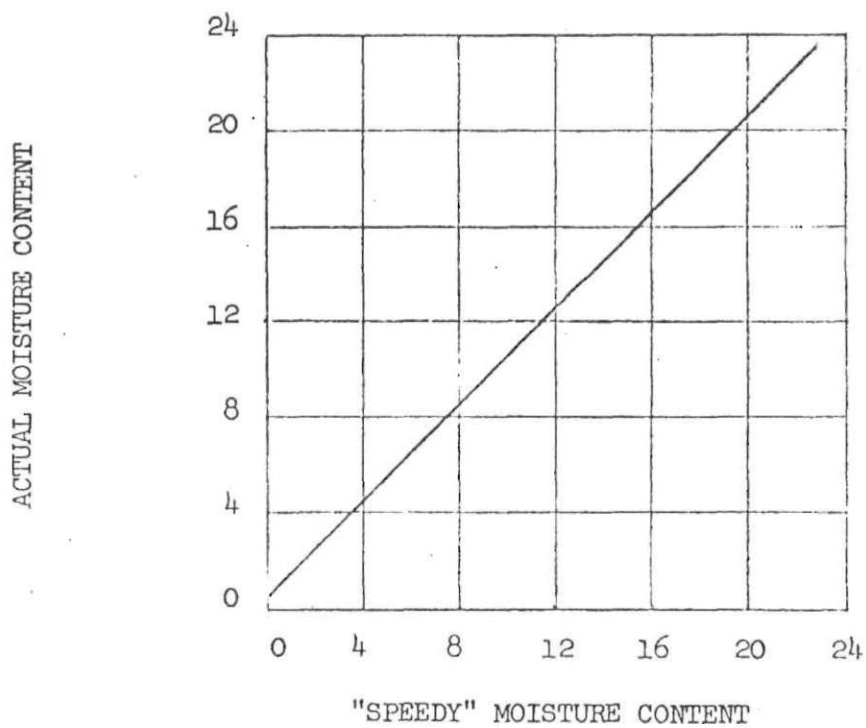

Fig.10. "Speedy" Calibration for Soil B

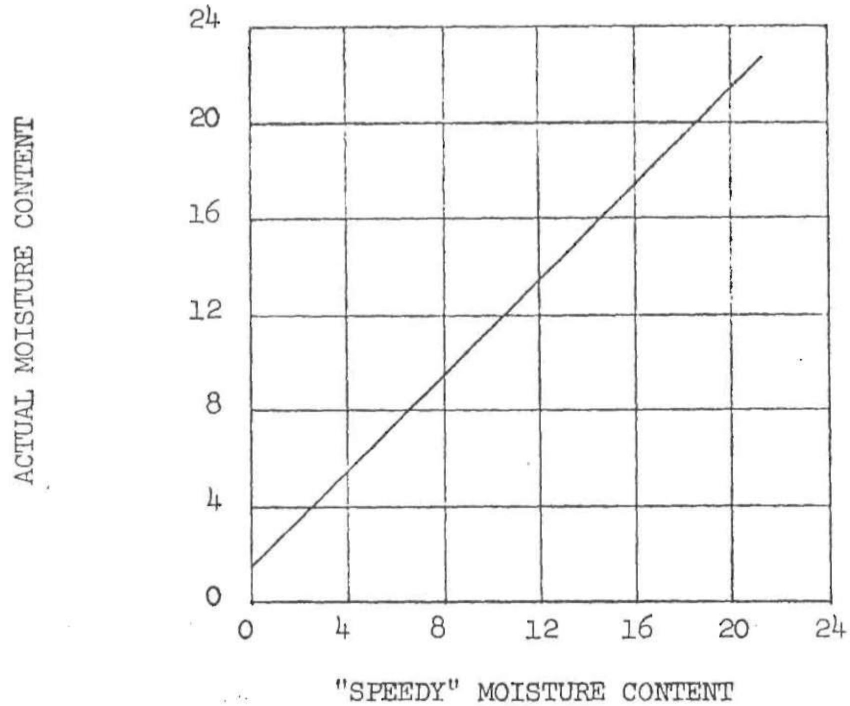

Fig. 11. "Speedy" Calibration for Soil C

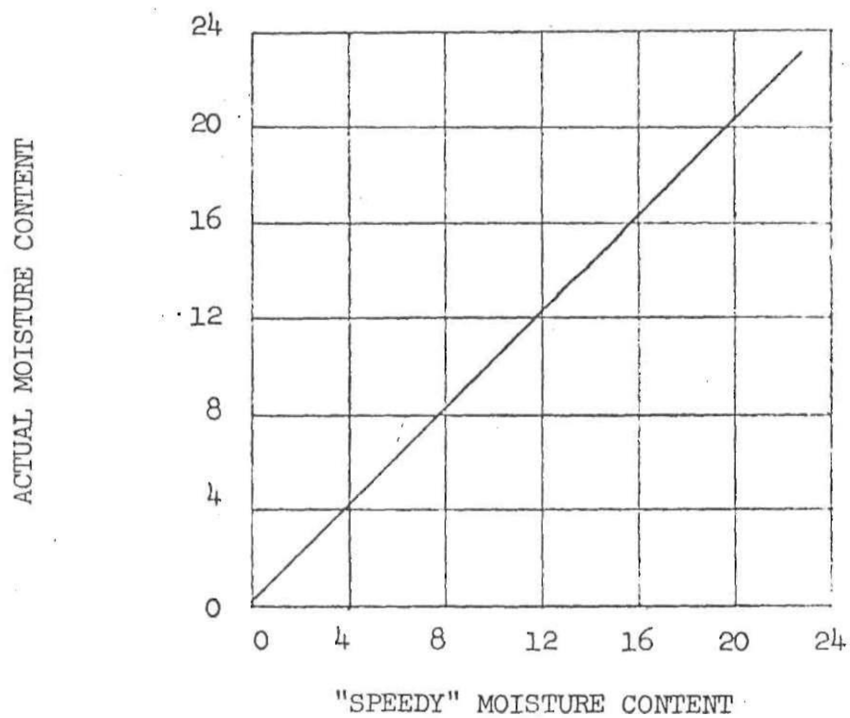

Fig. 12. "Speedy" Calibration for Soil D

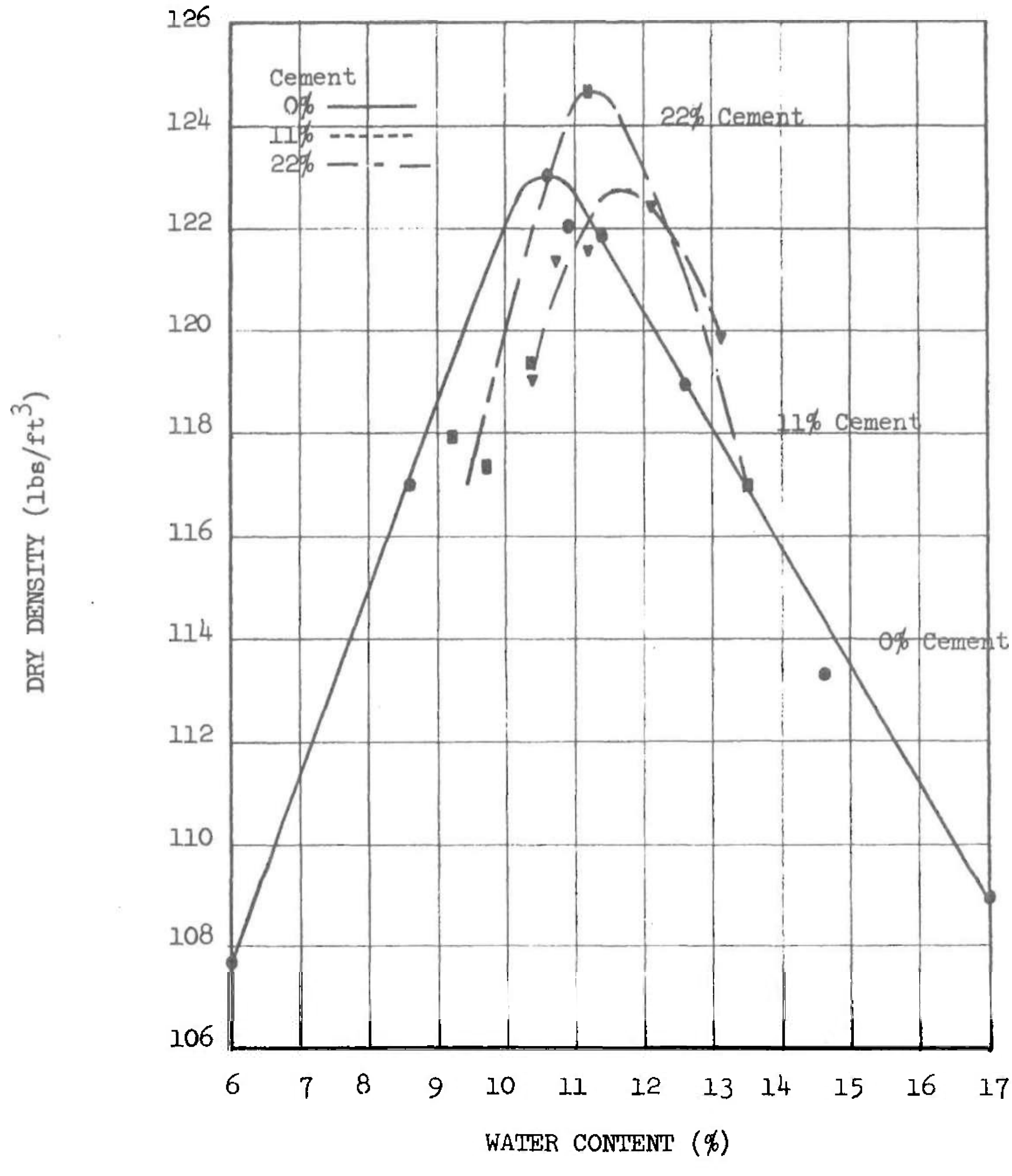

Figure 13. Moisture-Density Relationship Soil A.

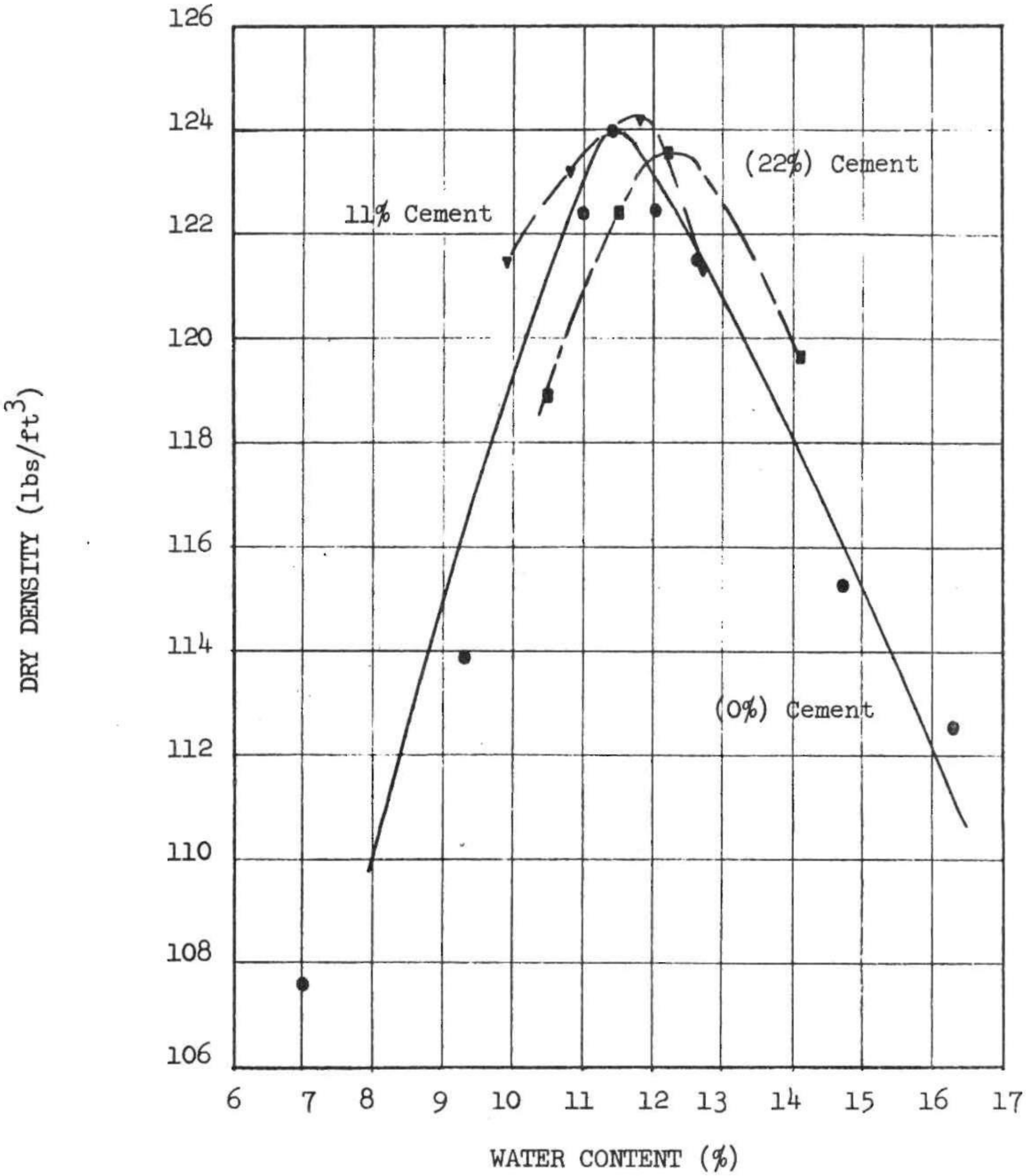

Figure 14. Moisture-Density Relationship Soil B.

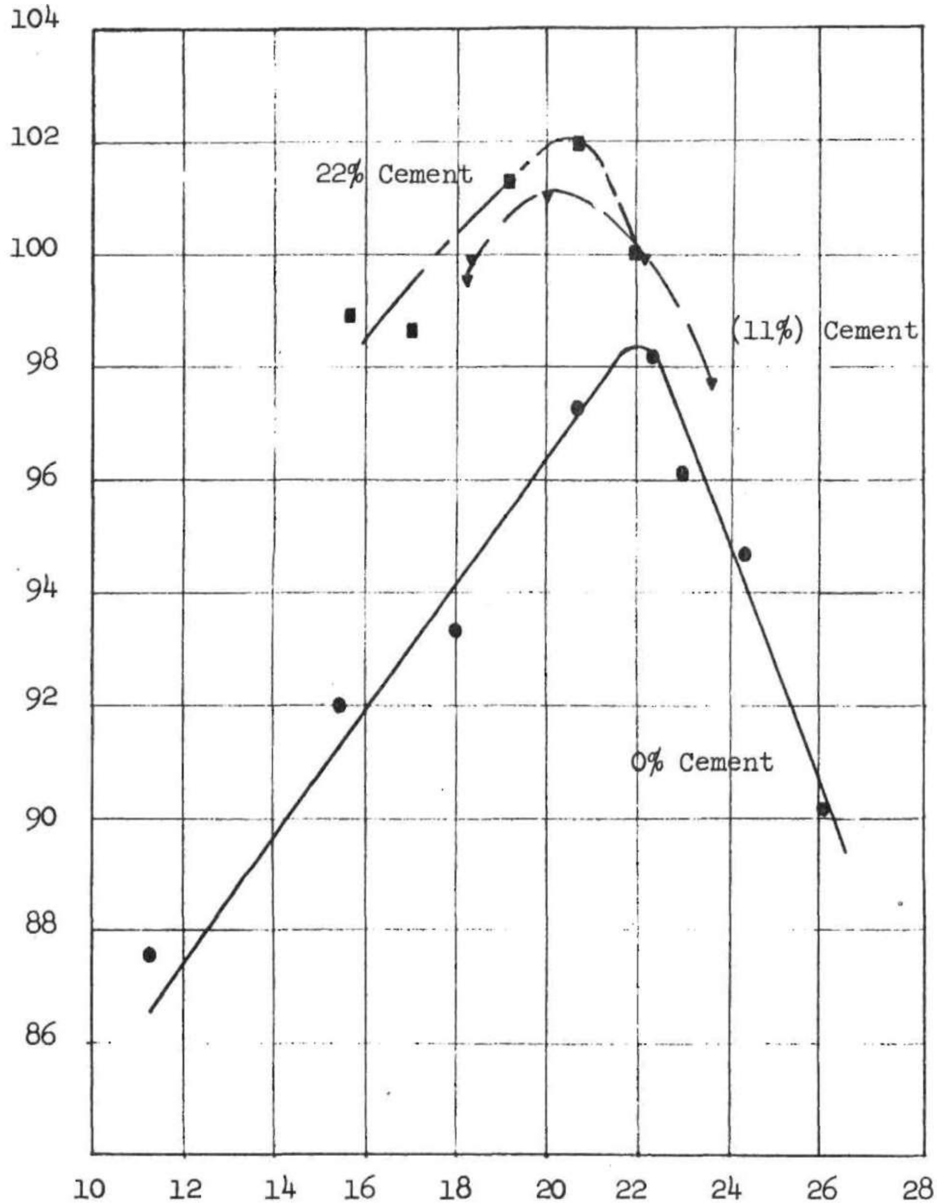

Figure 15. Moisture-Density Relationship Soil C.

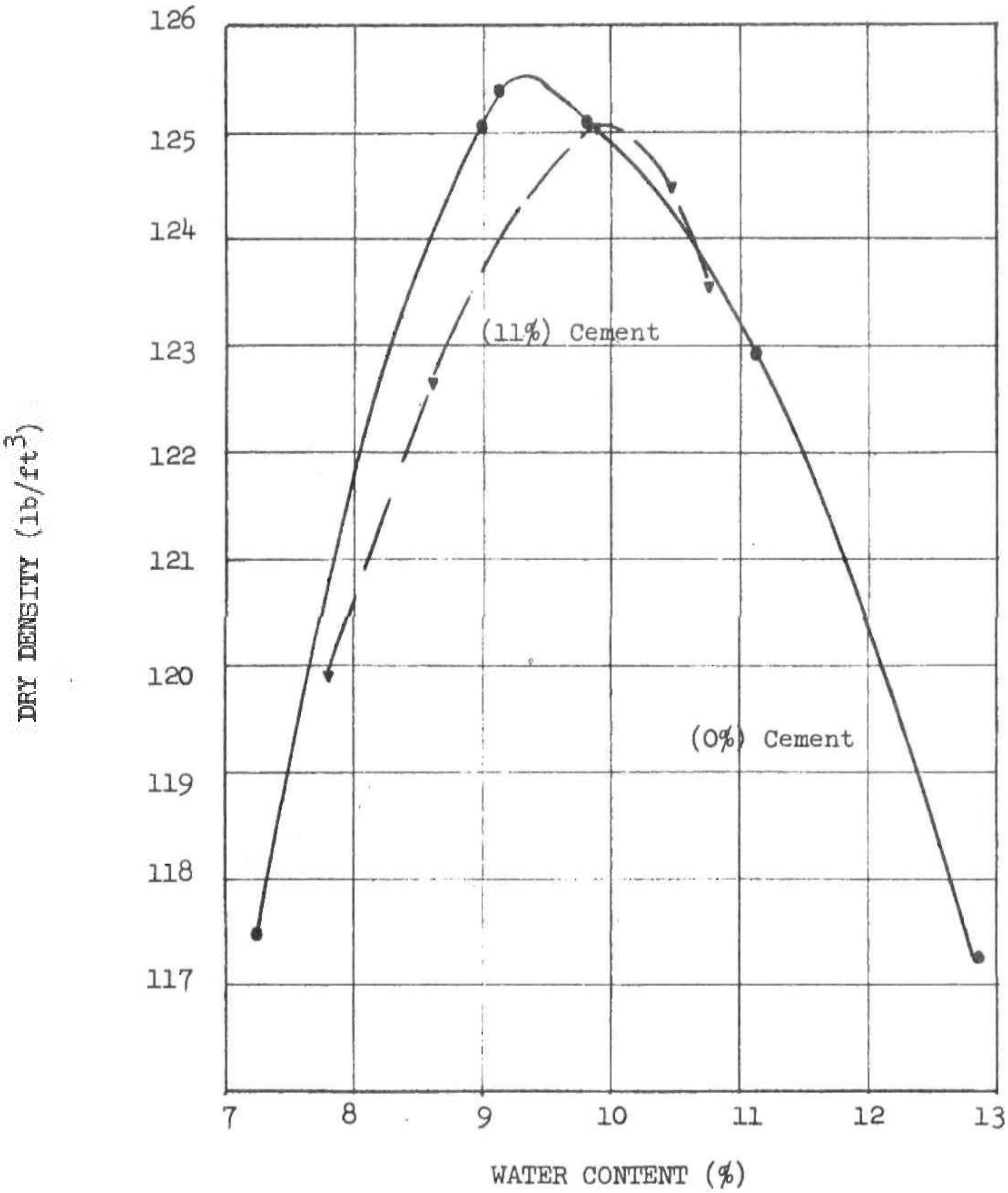

Figure 16. Moisture-Density Relationship Soil D.

would be as near ideal as possible to permit the specimen to be accessible for numerous observations, and show any cracks that may develop.

Several methods were tried: coating the entire specimen with a thin coating of RC-3 (rapid curing, Grade 3, cutback asphalt), placing the specimen in plastic freezer bags, and wrapping the specimen with a tight-fitting saran wrap. The RC-3 coating was too time-consuming and would not produce the proper water retention in the specimen. The plastic freezer bags were too loose fitting, resulting in poor observation of the specimen. The saran wrap, which was selected for this experiment, kept the moisture content constant in the specimen, involved a minimum of time in placing and due to its clear, glass-like and tight-fitting properties, permitted excellent observation of the specimen. This wrapping process is shown in Fig. 17. Moisture determination made on specimens wrapped with saran wrap showed 100 per cent moisture retention within an accuracy of 0.01 grams.

Figure 17. Wrapping Process for Curing.

CHAPTER IV

TESTING PROCEDURES

General

The factors studied were clay content (based on size) present in the soil, cement and moisture contents (based on weight), curing and temperature differential existing in bases. These factors were obtained from theoretical and empirical knowledge. Relationship of these factors to cracking are as follows:

Clay Content Present in the Soils

The higher the clay content and type of clay a soil possesses, the more that soil would behave like that clay, which for an expansive clay would be large volume change and a great affinity for water. The ability of the clay particles to keep the water within themselves would thereby prevent sufficient cement hydration and upon the loss of water, due to evaporation, the soil would not be strong enough to resist the volume change. This could cause cracking.

Cement Content

Due to the autogenous shrinkage of Type I Portland cement (the actual loss of mass due to the chemical reaction caused by the induction of water to Portland cement), the higher the cement content the larger would be the weight loss which would result in cracking.

Moisture Content

The moisture content that would result in a minimum of cracking for different combinations of soil and Portland cement is not always the optimum found by the moisture-density relationship for maximum density.

Curing

The loss of moisture by evaporation will cause a decrease in volume, due to the stress in the mass caused by capillary tension, which results in cracking. Keeping the moisture in the soil by proper curing would reduce early cracking and would permit the soil structure to gain sufficient strength to resist shrinkage forces due to subsequent drying.

Temperature Differential

The temperature differential that exists in freshly placed bases in the field, which is around 70 deg. F. induces stresses that could cause cracking. This could be attributed to numerous factors:

1. Accelerated hydration on the upper surface due to the high temperatures.

2. Expansion and contraction of the soil resulting in a warping action.

3. The high temperatures on the upper surface forcing the moisture to a cooler region, the bottom.

Test Number I

To find the relationship of clay, moisture, and cement contents and curing the following test procedure was used:

1. For each of the four soils, two specimens, one 3 per cent below optimum moisture content and one 3 per cent above optimum moisture content, were compacted for each of 10 different cement contents. Cement percentages used were 0, 1, 2, 3, 5, 8, 11, 14, 18 and 22.

2. After compaction, the specimens were trimmed, removed from the mold, and wrapped with saran wrap for curing.

3. The specimens were then placed in curing racks in the laboratory and observed at specified periods to determine the presence of and/or the development of cracking. Comparison of the amount of cracking between different specimens was made through the use of photographs.

4. The specimens were retained inside the laboratory for a period of not less than five weeks. After this curing period the saran wrap was removed and the specimens were placed out-of-doors and subjected to atmospheric conditions. The temperatures ranged from 70 to 95 deg. F. and the rainfall during these testing months of June and July was about 2 inches above the normal 4.25 inches for the Atlanta area.

Test Number II

To find the relationship of temperature differential to cracking the following test procedure was used:

1. For each of the four soils, duplicate specimens were compacted at optimum moisture content and 3 per cent above optimum moisture content for each of the four cement contents, 0, 3, 8 and 22 per cent.

2. The specimens were trimmed and removed from the mold. One of each duplicate specimen was wrapped with saran wrap while the other was left unwrapped.

3. The specimens were then immediately placed in the temperature differential apparatus, and subjected to temperature differential of 70 deg. F. from the top to the bottom of the specimens.

4. After a period of 24 hours, the specimens were removed from the temperature differential apparatus and photographs were made of the specimens.

Preparation

1. The amount of soil needed was calculated from moisture density data, removed from storage barrels, and placed in the mixing bowl. The soil was then mixed until homogeneous.

2. The hygroscopic moisture content of the soil was estimated by the use of a "speedy" moisture tester manufactured by the Alpha Lux Company, Inc. At this time a moisture sample of the soil was placed in a 10 oz. can, dried in an oven at 230 deg. F. for 24 hours and the actual water content determined. If the actual hygroscopic moisture content was more than $\pm$ 1.0 per cent different from the "speedy" reading, the specimen.was discarded and a new one made.

3. The required amount of cement was then weighed to the nearest 0.01 pound, and mixed with the soil until homegeneous. The amount of cement used was calculated as a per cent of the weight of dry soil. For example, if the weight of the dry soil was 50 lbs. and five per cent content was desired, 2.50 lbs. of cement would be added.

4. The amount of water to be added was weighed to the nearest 0.01 pound and slowly added while mixing to the soil-cement mixture. The amount of water used was calculated as a per cent of the total dry weight of the soil and cement. For example, if the weight of the dry soil was 50 lbs., the weight of the cement was 2.50 lbs., and the desired water content was 10 per cent then 5.25 lbs. of water would be needed.

5. The contents of the bowl was then mixed by the Read Standard Grant mixer for a period of 45 seconds. The blade and sides of the bowl were scraped and the contents mixed for another 45 seconds.

Compaction

1. The amount of the soil-cement mixture needed for a two-inch layer was calculated and placed in the mold. The soil was compacted by allowing an 11-pound rectangular hammer to be dropped 123 times from a height of 12 inches above the surface of the soil (See Fig. 2 for details of the compaction equipment). This procedure was repeated for each of the three layers, but allowance was made for enough excess on the top layer to be scraped off level with the top of the mold. During compaction the mold was moved horizontally to insure that the number of blows would be evenly distributed throughout the entire area of each layer. This also prevented irregularities in layer thickness.

2. The compacted specimen was removed from the mold, placed on a 3/4 in. x 20 in. x 9 in. plywood board and weighed to the nearest 0.1 pound. To simulate field-curing, the specimen was completely sealed by wrapping it with transparent saran wrap. The specimens were placed in storage bins inside the laboratory for periodical observation. These storage bins are shown in Fig. 18.

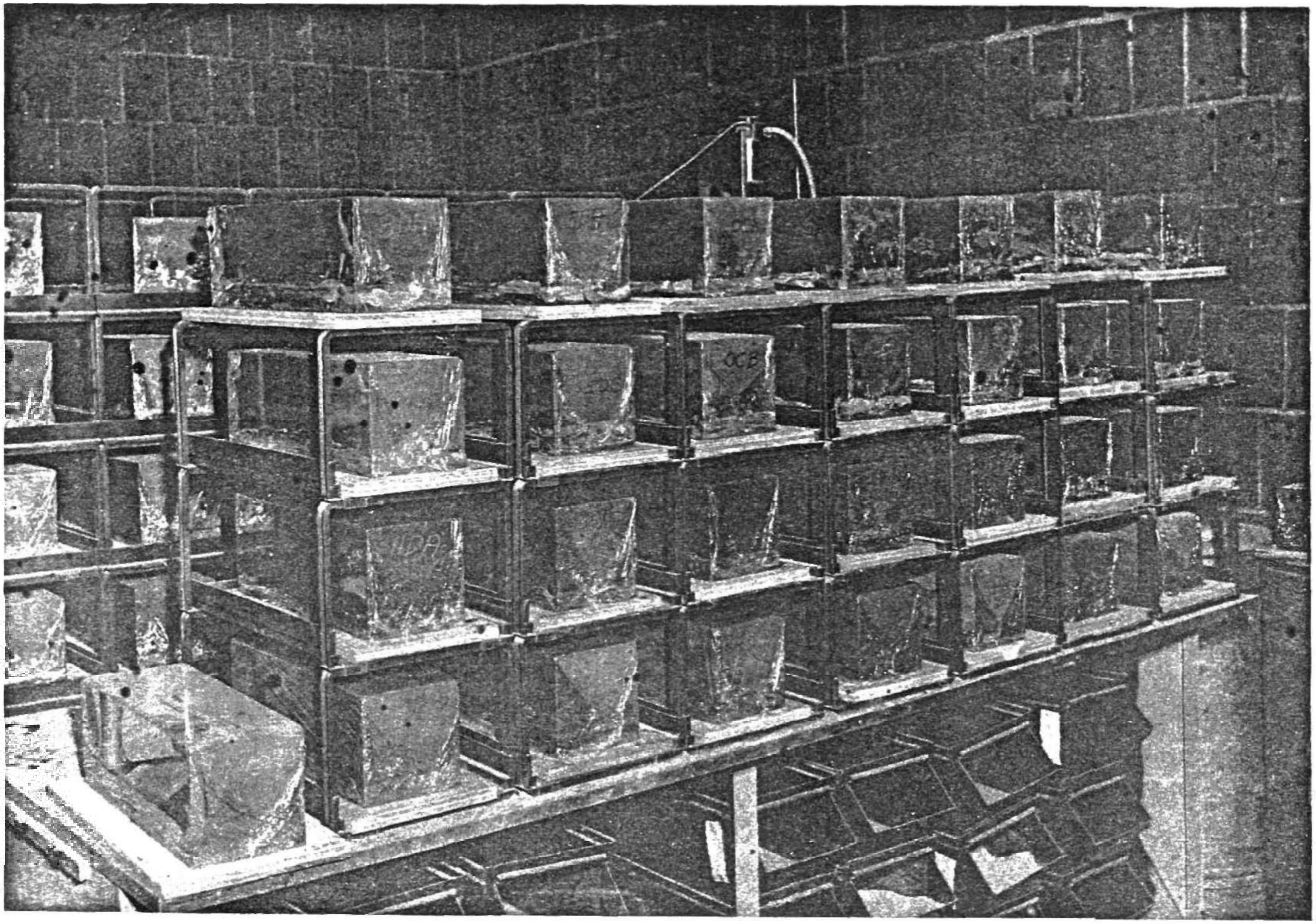

Figure 18. Storage Bins.

CHAPTER V

EVALUATION OF TEST RESULTS

The results obtained from Test No. I, which was conducted to find a relationship of clay, moisture, and cement content to cracking, were both numerous and conclusive. During a five-week curing period with observations being made periodically, no evidence of cracking was detected in the specimens. It was concluded therefore, that the internal action of Type I Portland cement does not by itself cause cracking. Pictures made of these specimens immediately after the curing material was removed are shown in Figs. 19 - 21.

From the periodical observations, it was found that with increasing cement contents more moisture appeared to be retained within the specimen. The low cement content specimens (0-3 per cent) showed large amounts of moisture collected on the inside of the curing material. These findings were similar for all four soils used in this test. Actual moisture measurements were not made because specimens were to be used in other phases of the test.

After removal of the curing jackets, all of the specimens for the four different type soils with low cement contents and moisture content 3 per cent above optimum, cracked within 24 hours.

Observations made of the specimens while being exposed to weathering showed that varying the moisture content 3 per cent above or 3 per cent below could result in detrimental effects to the durability of the specimens. Soils B and C, with high cement contents, showed good

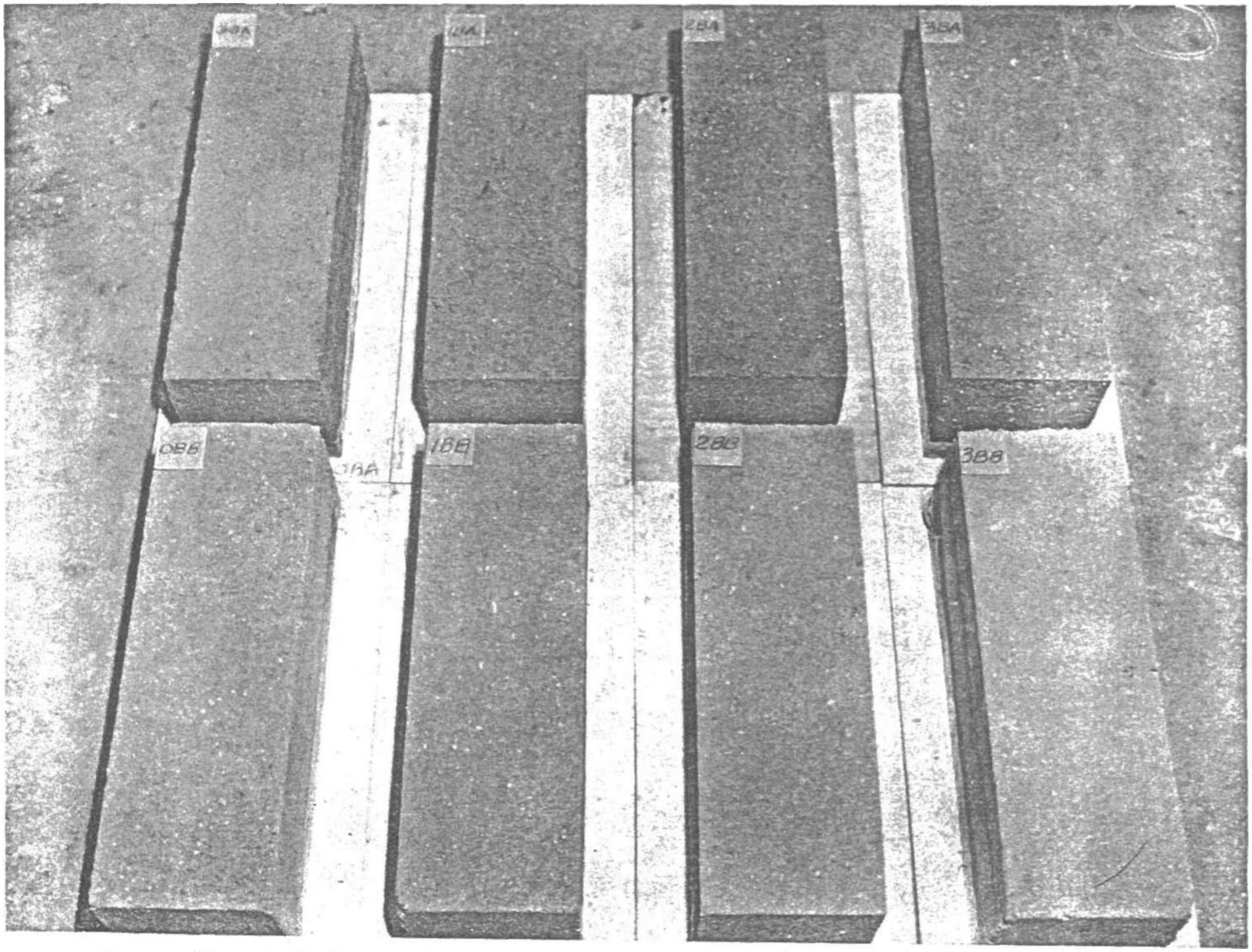

Figure 19. Soil B Specimens, with 0, 1, 2 and 3 Per Cent Cement at 3 Per Cent Below Optimum Moisture, After 5-Week Curing Period.

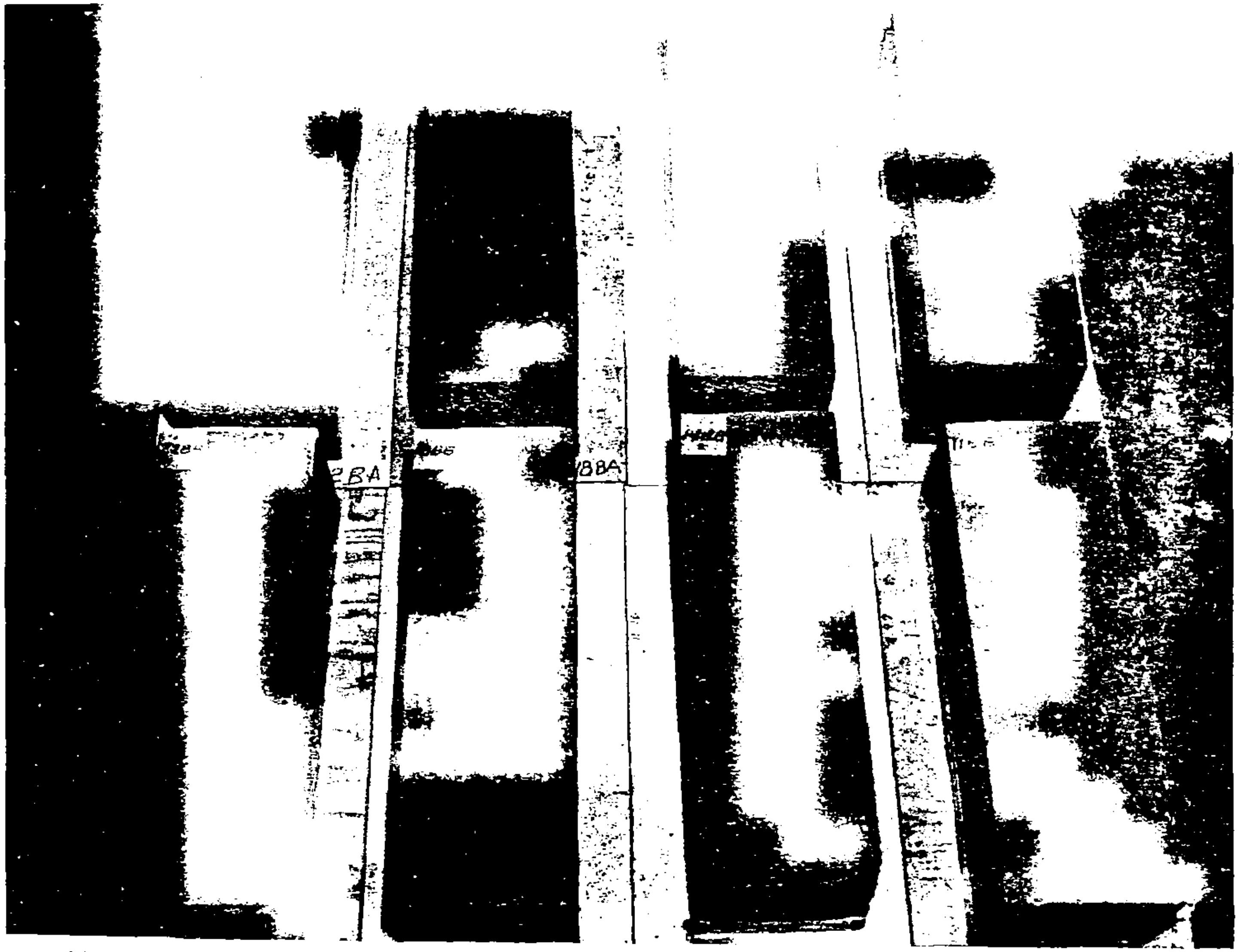

Figure 20. Soil B Specimens, with 11, 14, 18 and 22 Per Cent Cement at 3 Per Cent Above and 3 Per Cent Below Optimum Moisture, after 5-Week Curing Period.

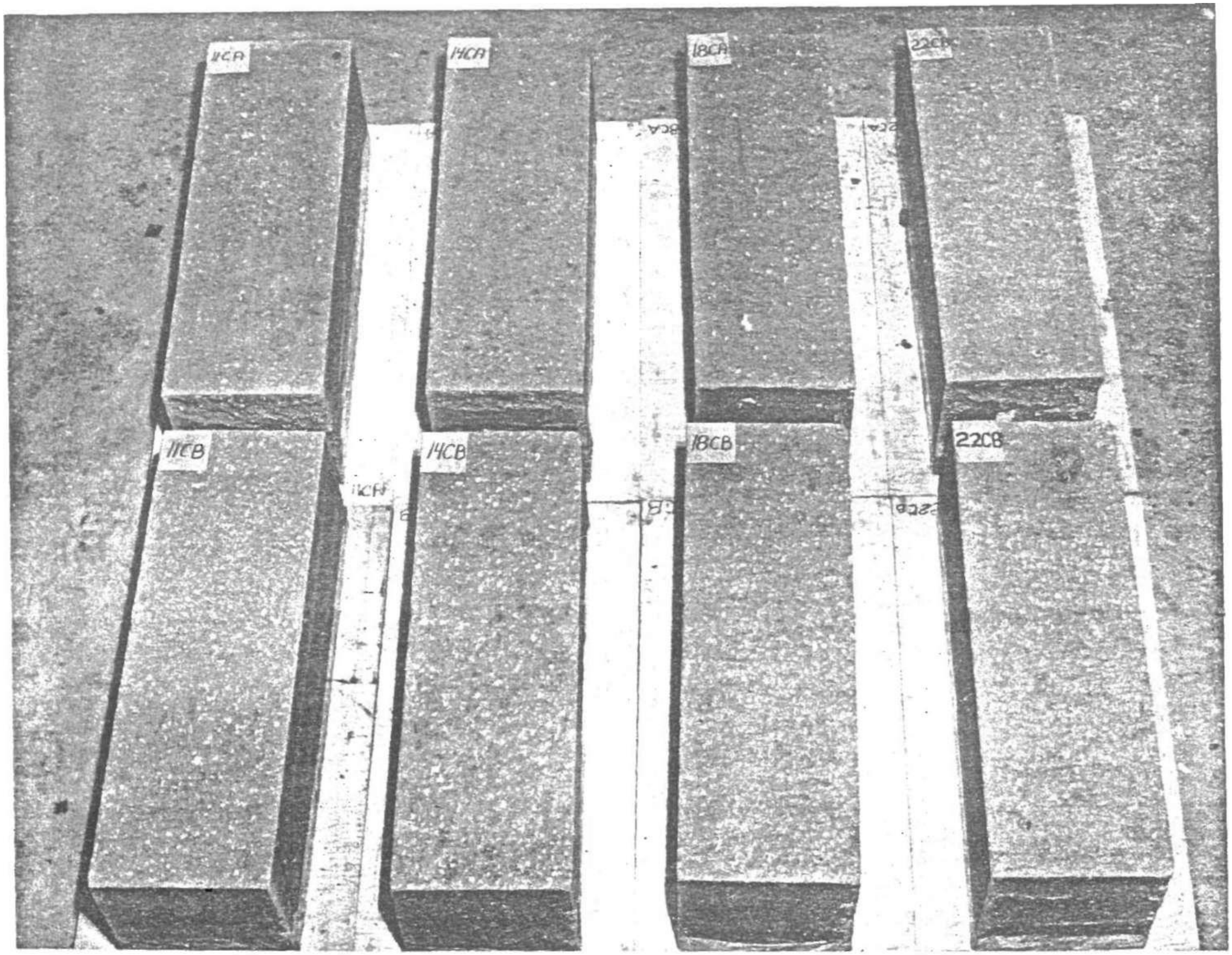

Figure 21. Soil C Specimens, with 11, 14, 18 and 22 Per Cent Cement at 3 Per Cent Above and 3 Per Cent Below Optimum Moisture After 5-Week Curing Period.

durability and were unaffected by heavy rains if they were compacted at 3 per cent above optimum moisture content but were very badly pitted if they were compacted 3 per cent below optimum moisture content. For the low cement contents the reverse was true, but it was not nearly as noticeable. The more friable soils, Soils A and D, showed this same relationship but in a much smaller degree. Pictures of these samples are shown in Figs. 22 - 24.

This same relationship was found from research on permissible moisture content variation from optimum conducted during the year 1938. The most important point shown by this early research is the following conclusion taken from the report.[13]

> The optimum moisture content (point at which maximum density is obtained) as shown by the standard moisture density test is reasonably in agreement with the optimum moisture contents at which maximum durability and maximum strength are obtained. For sand soil-cement mixtures, moisture contents, at the optimum (for maximum density) are ideal for best all-around durability and strength; but for silt soils and clay soils the moisture content for best all-around durability and strength is slightly wetter than the optimum quantity.

Graphs plotted from values given in Tables 5 - 10 are shown in Figs. 25 - 28. These graphs show the dry density remaining almost constant for each soil with an increasing cement content when compacted 3 per cent above optimum moisture content. When the soils were compacted 3 per cent below optimum moisture content, each soil except C showed a decrease in dry density with increasing cement content and then a slight increase in dry density with further increasing in cement content. Soil C, due to its light weight characteristics, was very sensitive to changing cement contents thereby resulting in widely varied dry densities. These graphs illustrate further how densities can be affected by varying

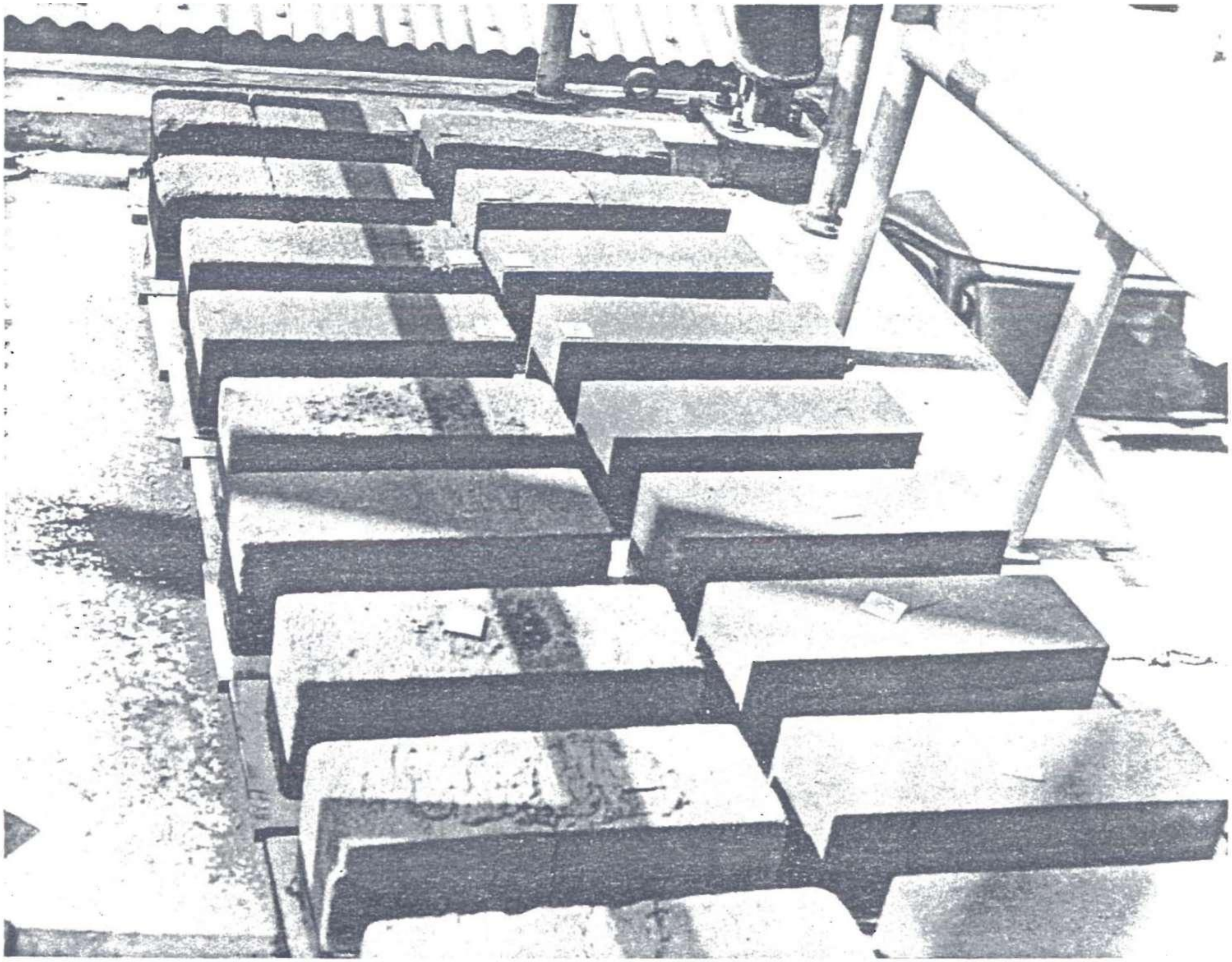

Figure 22. Soil A Specimens Being Subjected to Outside Exposure.

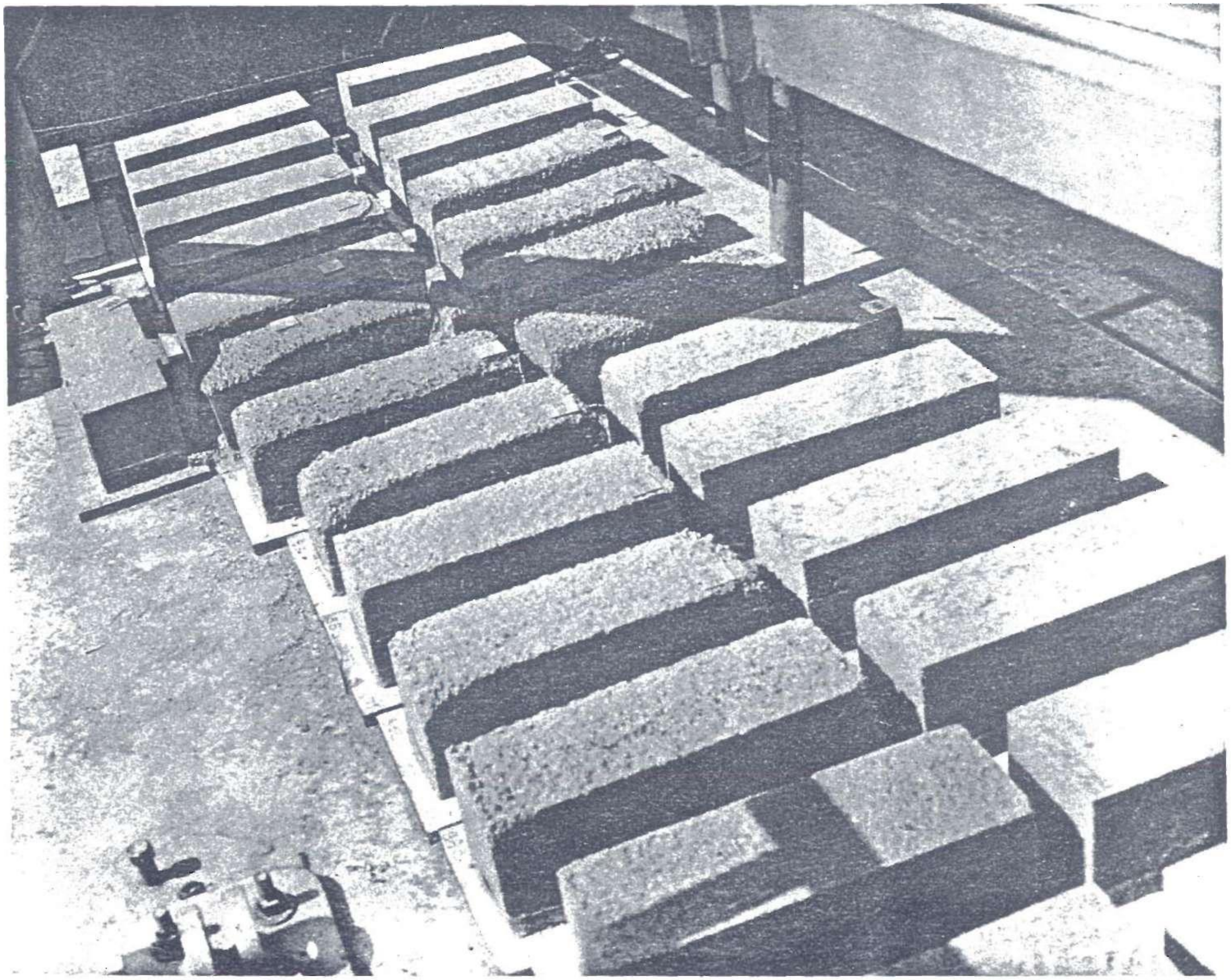

Figure 23. Soils B and C Specimens Being Subjected to Outside Exposure.

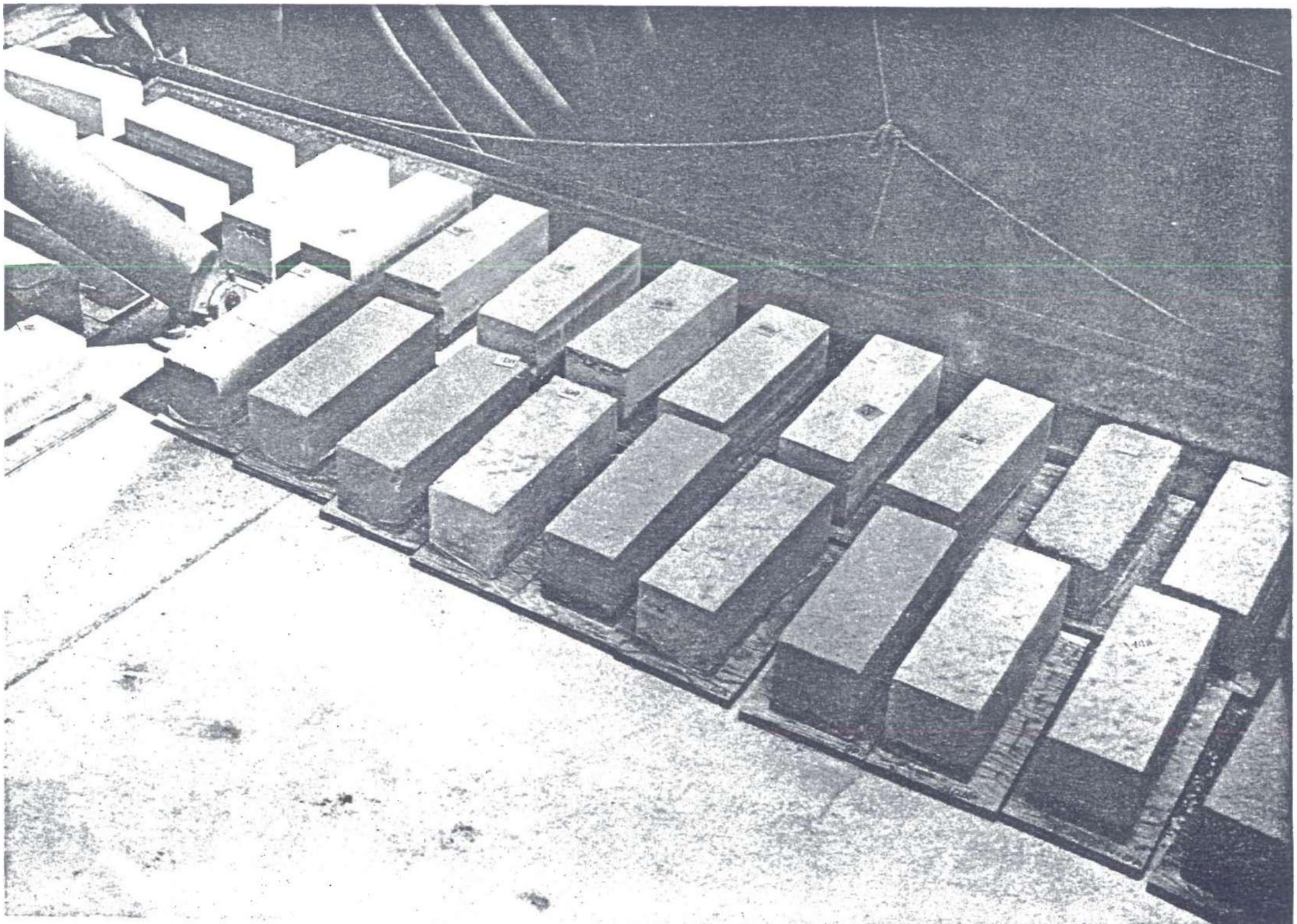

Figure 24. Soils C and D Specimens Being Subjected to Outside Exposure.

Table 5. Test No. 1 Specimen Data (Soil A)

Specimen No.	% Cement	Water Content Desired	Water Content Actual	Density Wet	Density Dry
OAB	0	7.6	7.6	128.7	119.6
OAA	0	13.6	13.1	136.3	120.5
1AB	1	7.6	7.6	122.7	114.0
1AA	1	13.6	13.6	134.9	118.8
2AB	2	7.6	8.0	115.3	106.8
2AA	2	13.6	13.5	134.4	118.4
5AB	5	7.6	7.6	114.9	106.8
5AA	5	13.6	13.9	134.2	117.8
8AB	8	7.6	7.6	106.5	99.6
8AA	8	13.6	13.5	136.5	120.3
11AB	11	7.6	7.7	112.6	104.5
11AA	11	13.6	13.1	127.9	113.1
14AB	14	7.6	7.3	106.4	99.2
14AA	14	13.6	13.7	133.9	117.8
18AB	18	7.6	7.1	106.0	99.0
18AA	18	13.6	13.1	137.0	121.1
22AB	22	7.6	7.4	104.8	97.6
22AA	22	13.6	12.7	134.1	119.0

Table 6. Test No. 1 Specimen Data (Soil B)

Specimen No.	% Cement	Water Content Desired	Water Content Actual	Density Wet	Density Dry
OBB	0	8.4	8.1	126.0	116.6
OBA	0	14.4	14.1	137.0	120.1
1BB	1	8.4	8.3	125.0	115.4
1BA	1	14.4	14.1	137.7	120.7
2BB	2	8.4	8.0	125.1	115.8
2BA	2	14.4	14.2	137.1	120.1
3BB	3	8.4	7.7	123.0	114.2
3BA	3	14.4	13.5	137.6	121.2
5BB	5	8.4	7.6	118.2	109.9
5BA	5	14.4	13.5	137.6	121.2
8BB	8	8.4	7.7	122.7	113.5
8BA	8	14.4	13.8	138.9	122.1
11BB	11	8.4	8.6	128.1	118.0
11BA	11	14.4	14.4	138.3	120.9
14BB	14	8.4	7.9	122.8	113.8
14BA	14	14.4	14.5	138.4	120.9
18BB	18	8.4	8.8	126.7	116.5
18BA	18	14.4	14.8	138.0	120.2
22BB	22	8.4	8.9	127.4	117.0
22BA	22	14.4	14.8	136.8	119.2

Table 7. Test No. 1 Specimen Data (Soil C)

Specimen No.	% Cement	Water Content Desired	Water Content Actual	Density Wet	Density Dry
0CB	0	19	14.6	106.8	91.7
0CA	0	25	24.0	118.3	95.9
1CB	1	19	20.0	115.7	96.0
1CA	1	25	26.0	120.0	94.8
2CB	2	19	20.0	116.3	96.9
2CA	2	25	25.2	120.2	96.0
3CB	3	19	20.0	117.1	97.6
3CA	3	25	26.0	121.0	96.0
5CB	5	19	19.7	122.0	101.9
5CA	5	25	26.0	120.4	95.6
8CB	8	19	20.0	119.8	99.8
8CA	8	25	26.0	121.2	96.2
11CB	11	19	19.5	113.6	95.1
11CA	11	25	26.0	121.0	96.0
14CB	14	19	19.8	115.8	96.7
14CA	14	25	26.0	120.8	95.9
18CB	18	19	19.1	117.2	98.4
18CA	18	25	26.0	120.5	95.2
22CB	22	19	19.9	113.6	94.7
22CA	22	25	25.4	122.5	97.7

Table 8. Test No. 1 Specimen Data (Soil D)

Specimen No.	% Cement	Water Content Desired	Water Content Actual	Density Wet	Density Dry
0DB	0	6.5	7.1	130.4	121.8
0DA	0	12.5	12.7	136.5	121.1
1DB	1	6.5	7.1	128.1	119.6
1DA	1	12.5	12.7	136.5	121.1
2DB	2	6.5	7.0	126.3	118.0
2DA	2	12.5	12.4	137.0	121.9
3DB	3	6.5	6.9	125.6	117.5
3DA	3	12.5	12.9	136.5	120.9
5DB	5	6.5	7.1	125.0	116.7
5DA	5	12.5	12.3	136.9	121.9
8DB	8	6.5	7.2	122.3	114.1
8DA	8	12.5	12.9	138.1	122.3
11DB	11	6.5	6.8	121.5	113.8
11DA	11	12.5	12.5	138.2	122.8
14DB	14	6.5	6.5	123.1	115.6
14DA	14	12.5	13.2	137.6	121.6
18DB	18	6.5	6.8	121.5	113.8
18DA	18	12.5	13.4	136.5	120.4
22DB	22	6.5	6.7	124.3	116.5
22DA	22	12.5	13.5	138.4	121.8

Table 9. Test No. 2 Specimen Data (Soils A & B)

Specimen No.	% Cement	Water Content Desired	Water Content Actual	Density Wet	Density Dry
0A	0	10.6	11.7	131.4	117.6
0A	0	10.6	11.4	130.8	117.4
3A	3	10.6	11.1	131.3	118.2
3A	3	10.6	10.1	124.8	113.4
8A	8	10.6	10.3	126.6	114.8
8A	8	10.6	9.8	118.3	107.7
8A	8	13.6	13.1	134.1	118.6
8A	8	13.6	12.7	132.1	117.2
0B	0	11.4	11.4	136.5	122.5
0B	0	11.4	11.4	138.7	124.5
0B	0	14.4	14.4	136.0	118.9
0B	0	14.4	14.4	134.5	117.6
3B	3	11.4	11.5	135.7	121.9
3B	3	11.4	11.7	136.7	122.4
8B	8	11.4	11.5	138.1	123.9
8B	8	11.4	11.5	131.7	118.1
8B	8	14.4	14.4	137.5	120.2
8B	8	14.4	14.8	138.5	120.6

Table 10. Test No. 2 Specimen Data (Soils A, B, C & D)

Specimen No.	% Cement	Water Content Desired	Water Content Actual	Density Wet	Density Dry
0C	0	22	22.9	119.6	97.3
0C	0	22	22.6	121.5	99.1
0C	0	25	25.8	116.7	92.8
3C	3	25	25.4	120.5	96.1
8C	8	22	22.3	121.7	99.5
8C	8	25	25.2	121.9	97.4
3C	3	25	25.5	120.4	95.9
0C	0	25	26.0	119.0	94.4
0D	0	9.5	10.1	138.9	126.2
0D	0	12.5	13.2	135.6	119.8
3D	3	9.5	10.3	136.8	124.0
3D	3	12.5	13.5	137.0	120.7
8D	8	12.5	12.9	137.4	121.7
8D	8	9.5	9.9	134.3	122.2
22C	22	25	25.9	122.2	97.1
22A	22	13.6	13.9	136.1	119.5
22B	22	14.4	14.7	134.9	117.6
22D	22	12.5	12.8	139.0	123.2

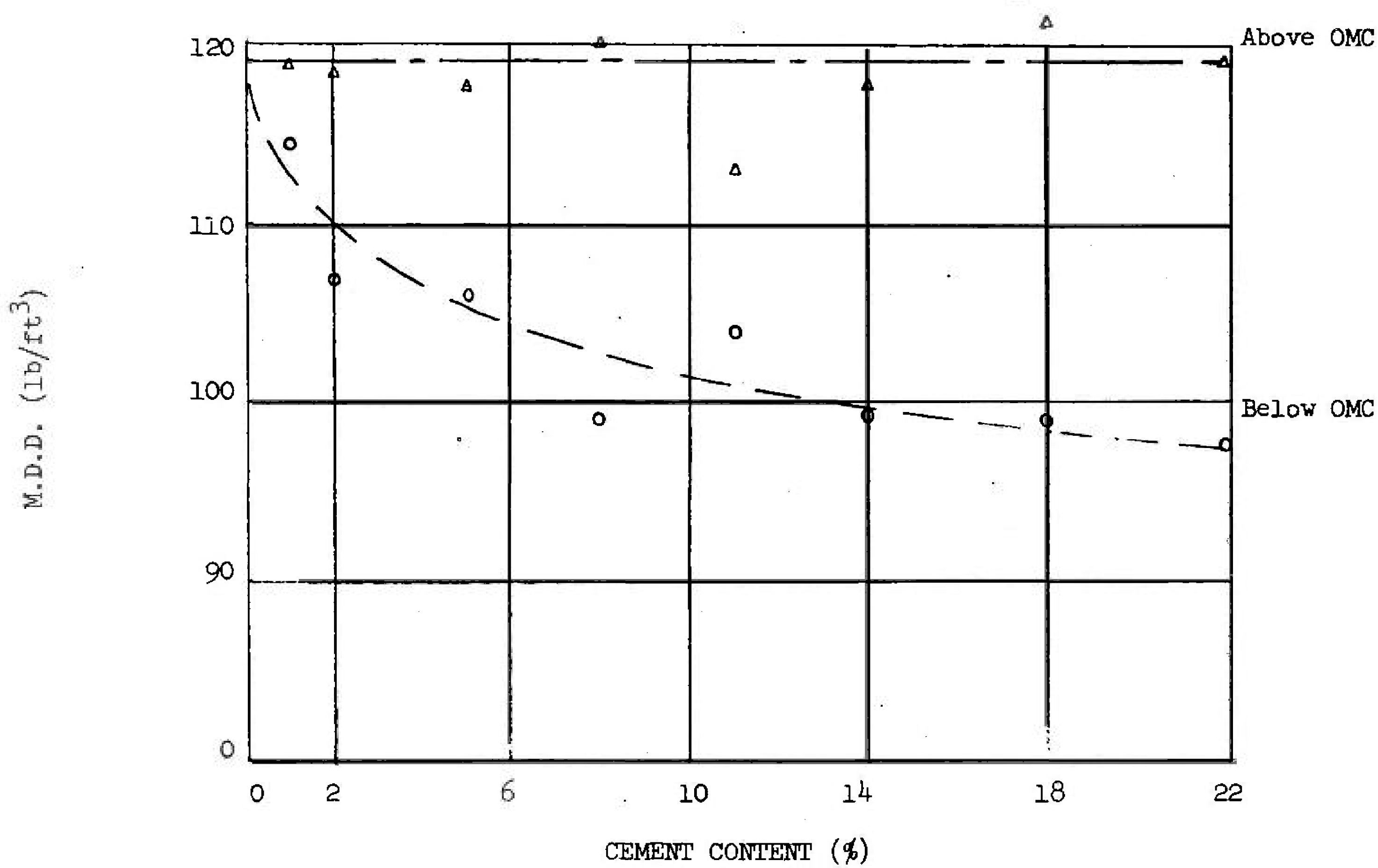

Figure 25. Variance of Maximum Dry Densities for Soil A.

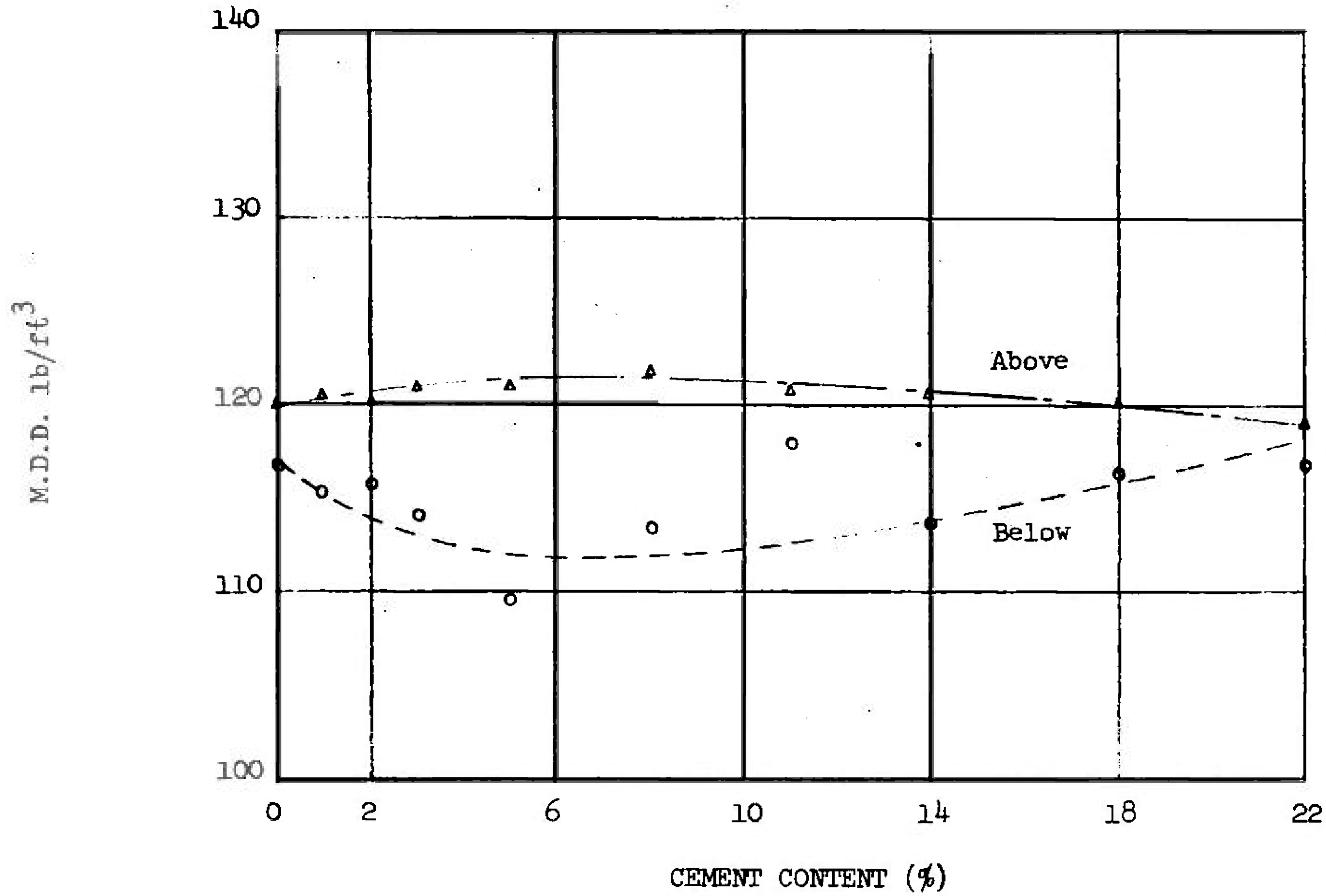

Figure 26. Variance of Maximum Dry Density for Soil B.

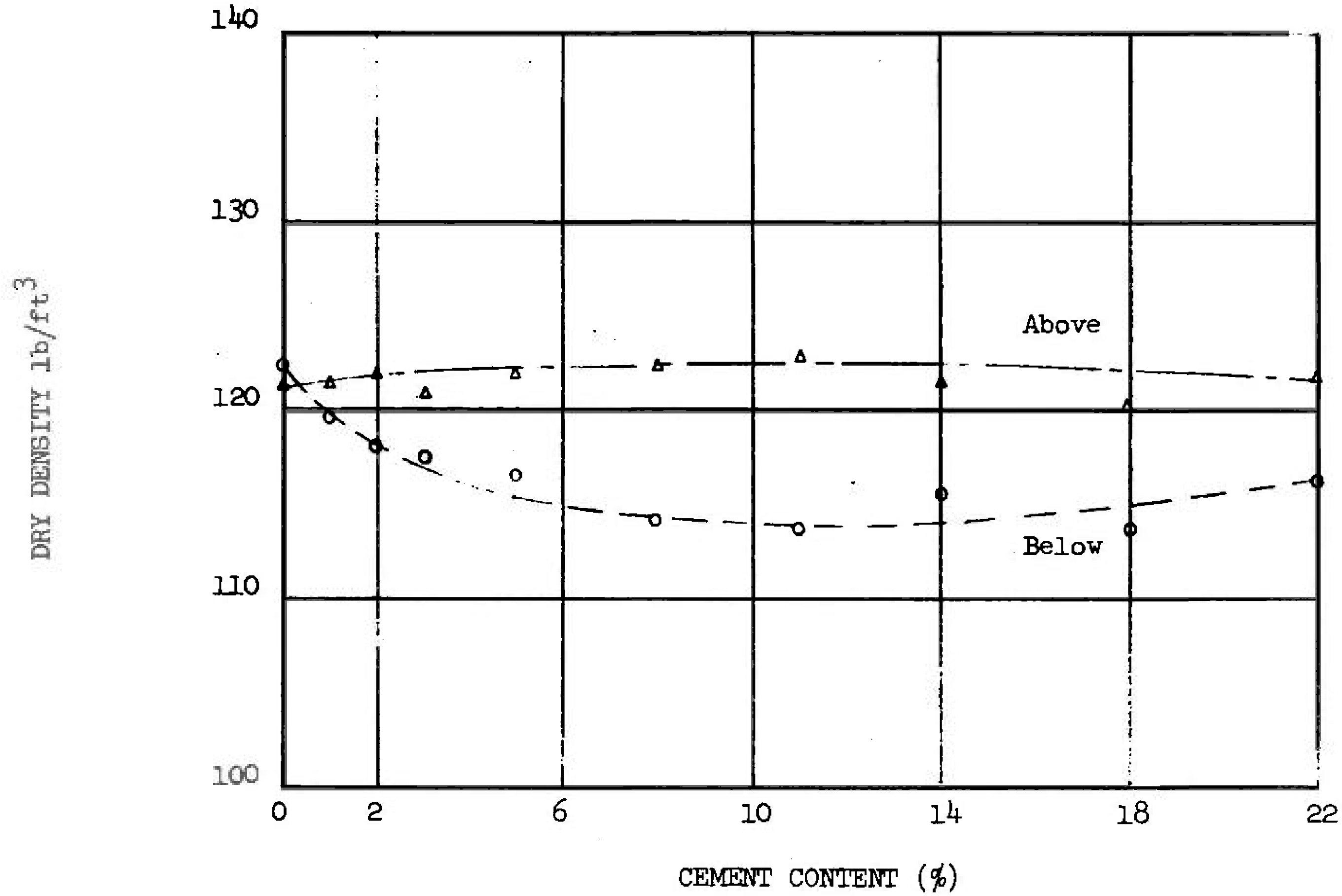

Figure 27. Variance of Maximum Dry Densities for Soil D.

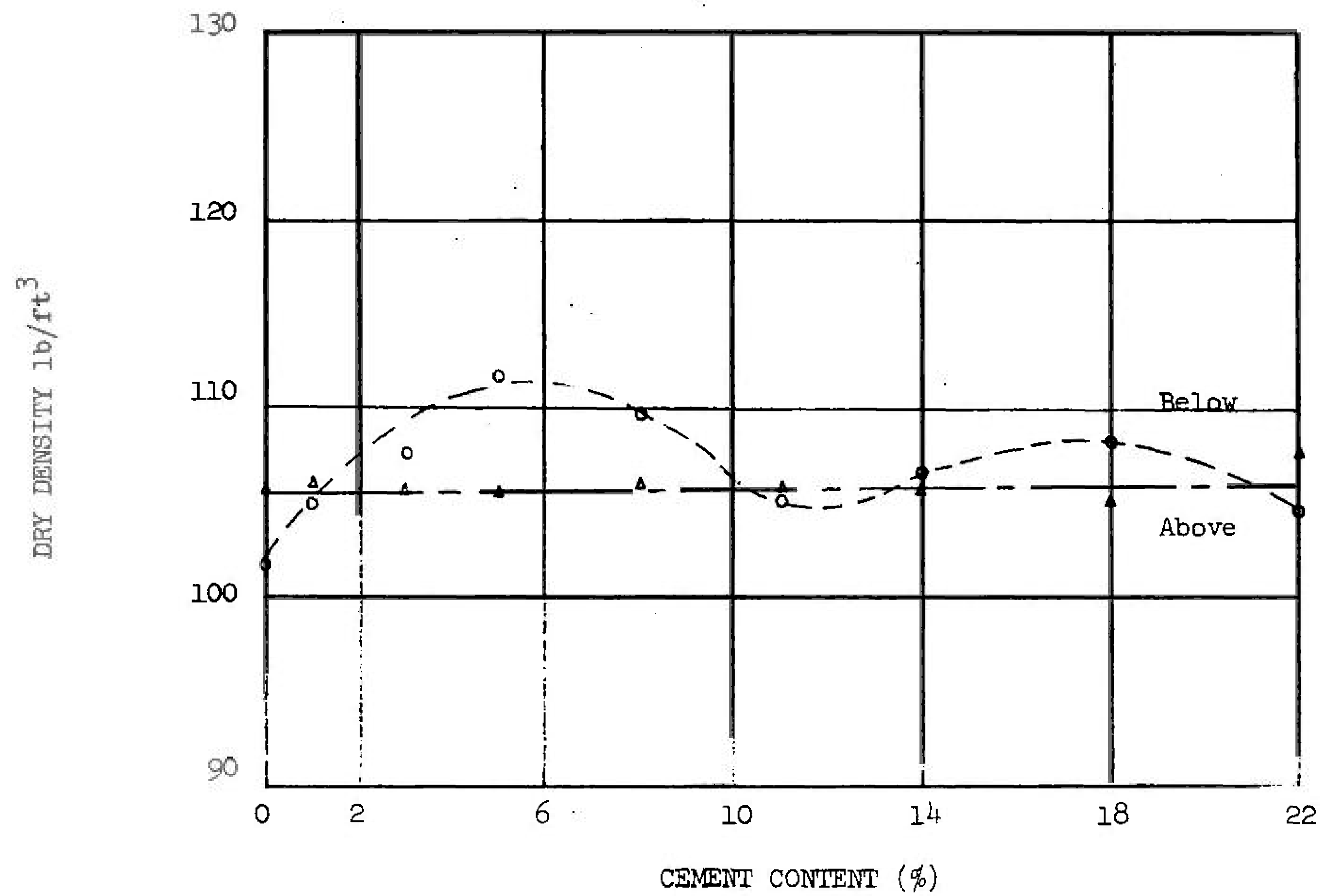

Figure 28. Variance of Maximum Dry Densities for Soil C.

moisture contents with different cement contents.

Test No. II, which was conducted to find a relationship of temperature differential to cracking, produced many rewarding results. One of the most outstanding of these was that the cracking occurred in specimens which were cured with a 100 per cent moisture retention, i.e., wrapped with a saran wrap curing jacket. There was less cracking observed in the specimens compacted at optimum moisture content. It was also observed that soils with the higher clay content developed the most cracking. After removing the cured specimens from the temperature differential apparatus, it was found that in all cases when moisture determination was made, the moisture content had decreased in the top about 4 per cent and increased at the bottom by about the same amount. The moisture determinations were made on specimens with zero per cent cement because of the problem of finding the moisture content of a soil-cement mixture after hydration has occurred. The remaining specimens displayed almost identical visual characteristics. This moisture displacement was attributed to the physical characteristics of water, thermal osmosis, which causes migration of the moisture to colder regions. In most cases where two identical specimens (except for curing) were subjected to the same temperature differential the poorly cured specimen developed more accelerated and serious cracking.

Soil A developed no cracks for the different cement content, cured or not cured, when the specimens were compacted at optimum moisture content. A few cracks did appear in the cured specimen compacted with 8 per cent cement and 3 per cent above optimum moisture content. The identical poorly cured specimen to the above developed no cracks. The cause of the cracks in the cured specimen was attributed to thermal osmosis where the water is migrating from the top of the specimen, where the higher temperature existed, causing shrinkage to occur. This development is shown in Fig. 29.

Soil B, compacted at optimum moisture content with 0 per cent cement content, and cured, developed no cracks. The twin to this specimen which was poorly cured showed large cracks across the top. The same results were observed when the cement content was held constant and the moisture content increased 3 per cent. These results are shown in Fig. 30. Using a 3 per cent cement content and the moisture content at optimum, the compacted specimen cured showed no cracks while the poorly cured specimen showed one very small crack across the top. Increasing the cement to 8 per cent and keeping the moisture content at optimum, the cured specimen developed one crack across the top, perpendicular to the length and about two inches deep, while the poorly cured specimen did not crack. Holding the cement content constant at 8 per cent and increasing the moisture to 3 per cent above optimum, both of the compacted specimens, cured and poorly cured, developed numerous cracks. Also, both specimens developed one crack about two inches deep across the top at mid-point. A picture of these specimens is shown in Fig. 31.

No cracks developed in Soil C for the varied cement contents when compared at optimum moisture content. Cracks did appear, however, in every case for the 0, 3 and 8 per cent cement contents, when compacted 3 per cent above optimum moisture content. These specimens are shown in Fig. 31.

The only cracks that developed while using Soil D were the speci-

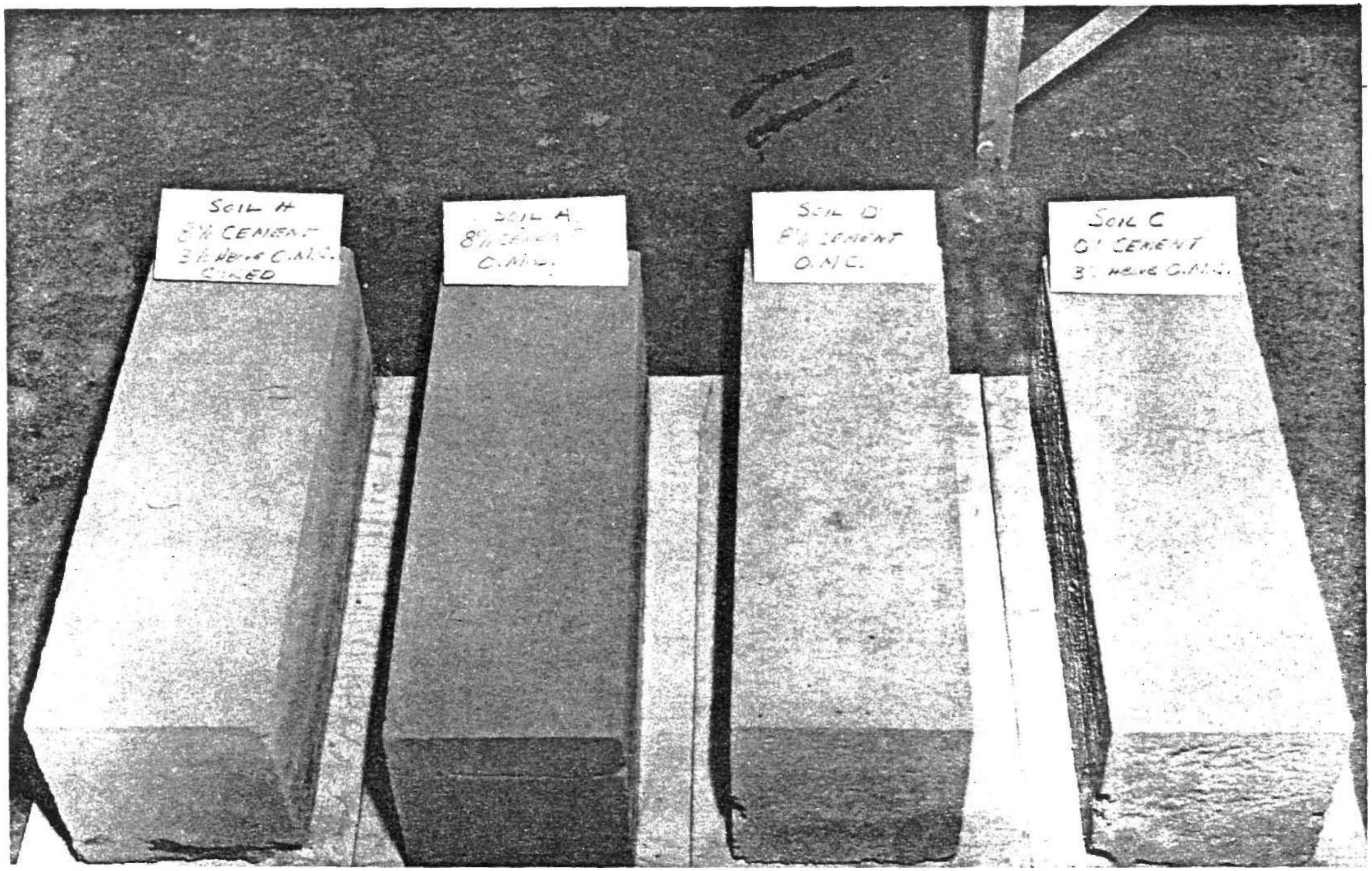

Figure 29. Soil A with 8 Per Cent at 3 Per Cent Above Optimum Moisture Content Cured and at Optimum Moisture Content Uncured; Soil D with 8 Per Cent Cement at Optimum Moisture Content Uncured; Soil C with 0 Per Cent Cement at 3 Per Cent Above Optimum Moisture Content Uncured, Being Subjected to a 70 Deg. F. Temperature Differential for 24 Hours.

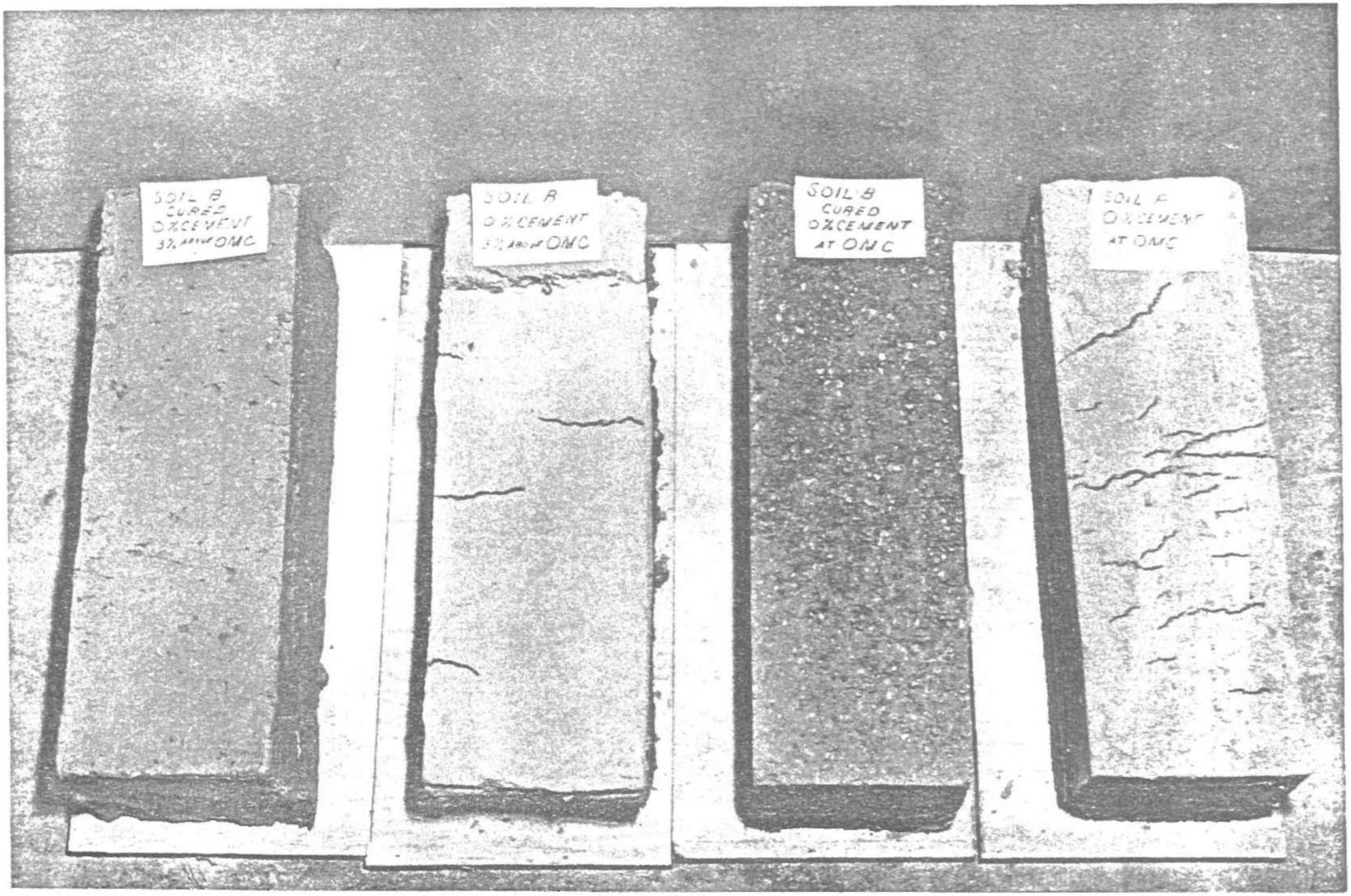

Figure 30. Soil B Specimen with 0 Per Cent Cement at 3 Per Cent Above Optimum Moisture Content Cured and Uncured, and at Optimum Moisture Content Cured and Uncured, Being Subjected to a 70 Dep. F. Temperature Differential for 24 Hours.

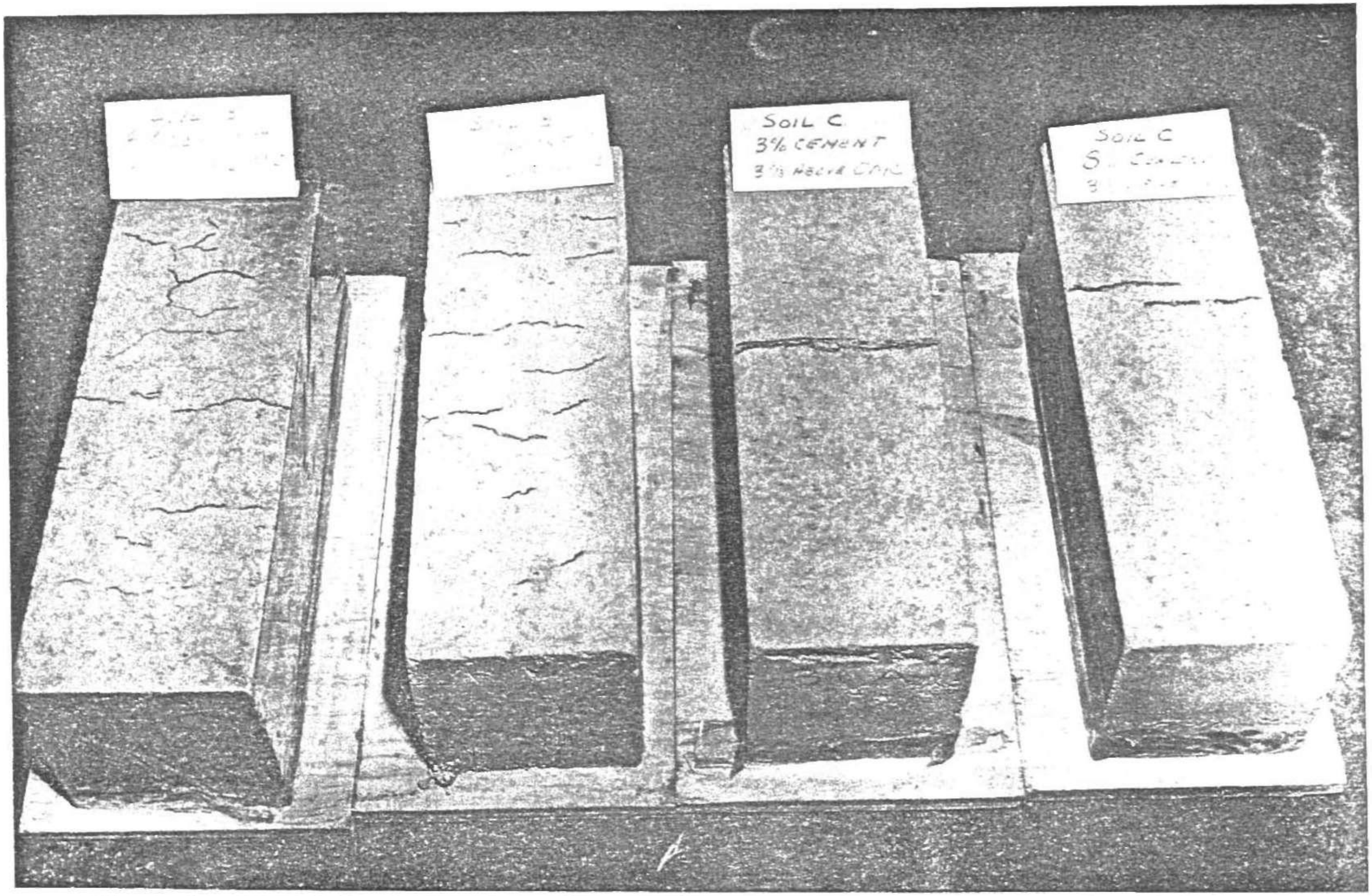

Figure 31. Soil B Specimen with 8 Per Cent Cement at 3 Per Cent Above Optimum Moisture Content Cured and Uncured; Soil C Specimens with 3 and 8 Per Cent Cement at 3 Per Cent Above Optimum Moisture Content Uncured, Subjected to a 70 Deg. F. Temperature Differential for 24 Hours.

mens compacted at 0 and 3 per cent cement with a moisture content of 3 per cent above optimum. The specimen with 3 per cent cement developed two cracks across the top about two inches deep at the mid-point. These specimens are shown in Fig. 32.

Fig. 33 shows all four different soils compacted at 3 per cent above optimum moisture content, and 22 per cent cement. These specimens developed no cracks.

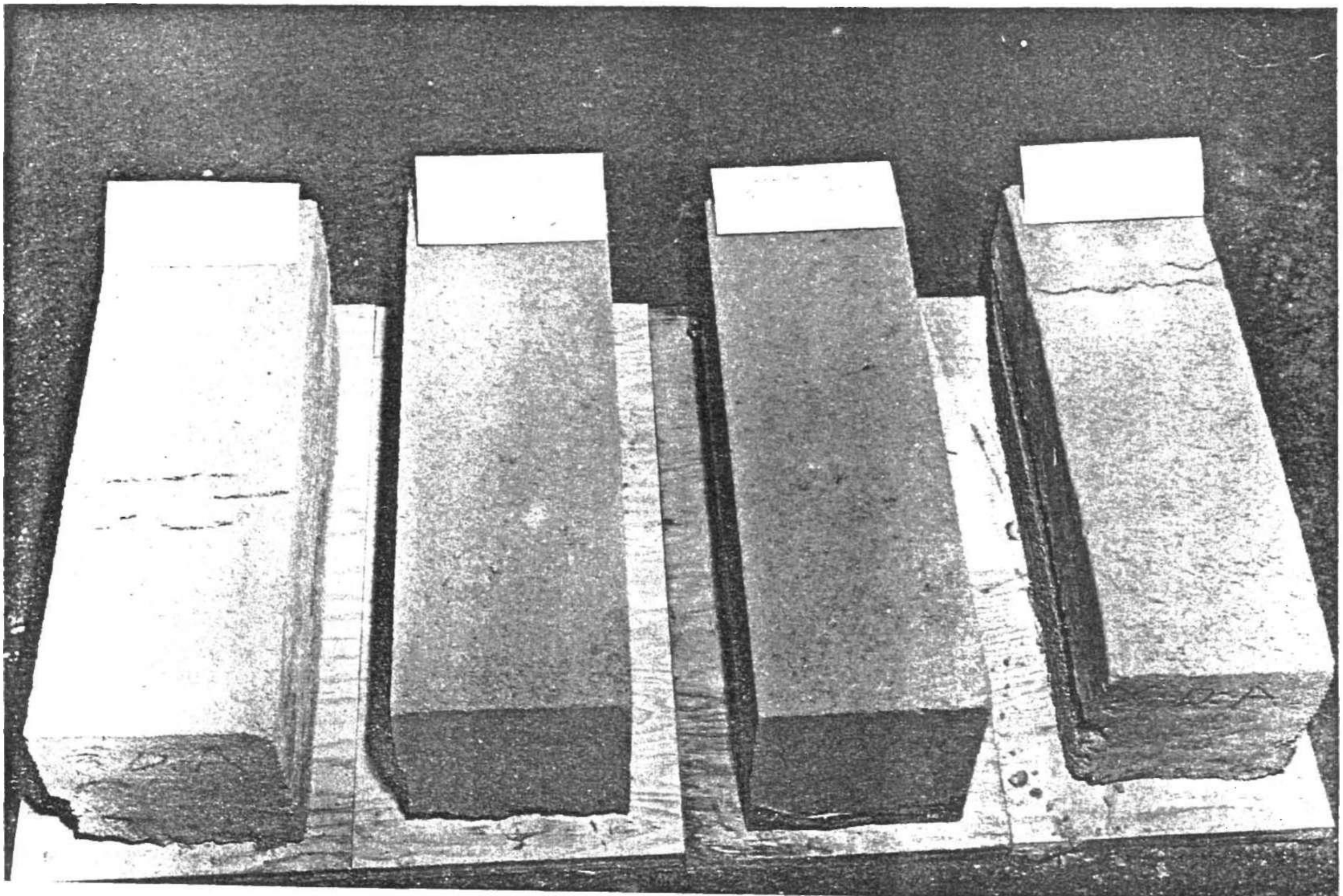

Figure 32. Soil D Specimens with 0 and 3 Per Cent Cement at 3 Per Cent Above and Below Optimum Moisture Content, Uncured, Subjected to a 70 Deg. F. Temperature Differential for 24 Hours.

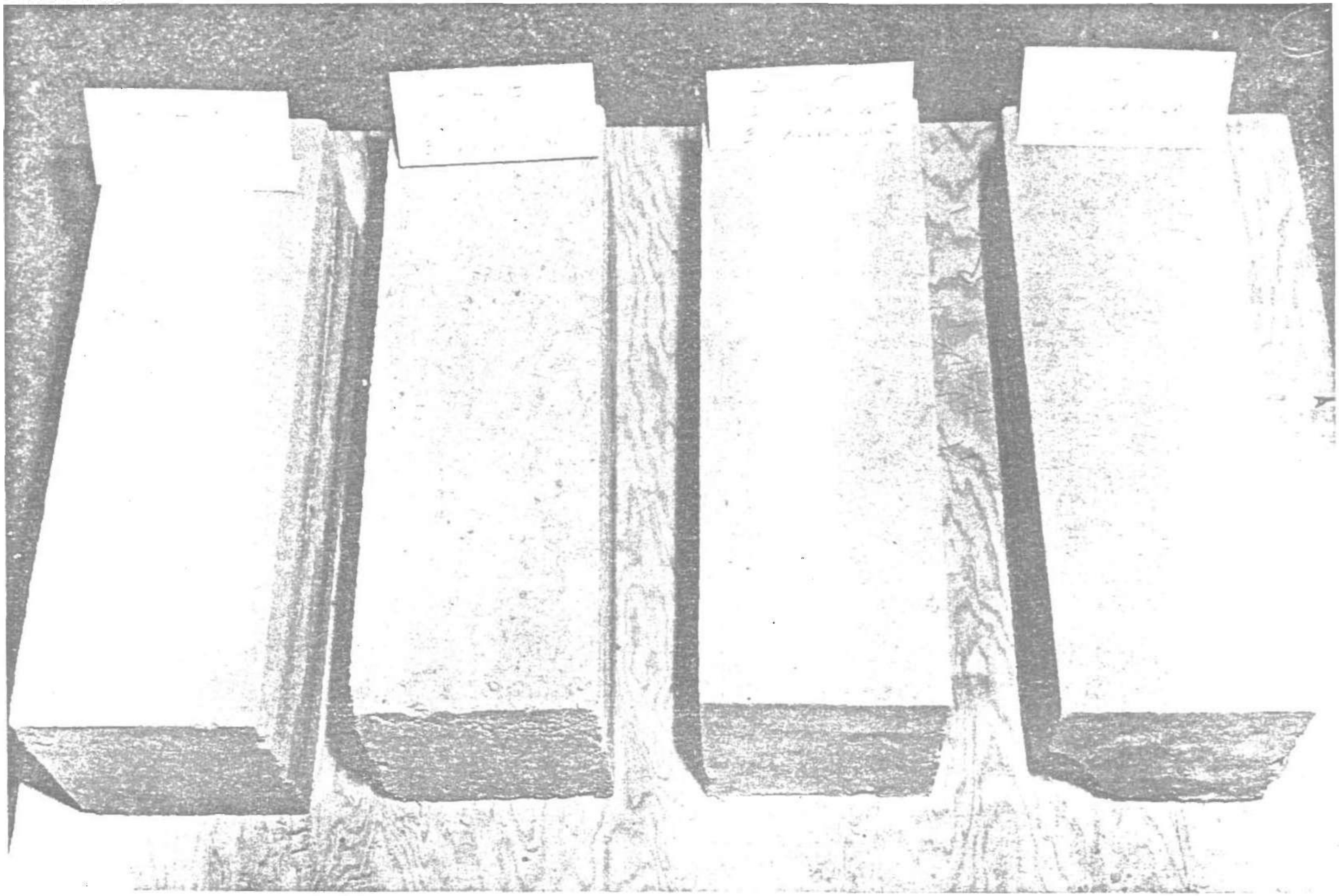

Figure 33. Soils A, B, C and D Specimens with 22 Per Cent Cement at 3 Per Cent Above Optimum Moisture Content and Uncured, Subjected to a 70 Deg. F. Temperature Differential for 24 Hours.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

From an evaluation of the test results, as given in Chapter V, the following conclusions are made:

1. Cracking that occurs in various types of soil-cement mixtures cannot be attributed entirely to the Type I Portland cement content existing in the respective mixtures.

2. The temperature differential existing in placed soil-cement bases i.e., the top surface at 140 deg. F. and the bottom surface at 70 deg. F., will in almost all cases cause a decreasing of the moisture content at the base courses upper surface even though 100 per cent moisture retention is accomplished. This temperature differential also causes an increase in the moisture content at the bottom layer.

3. The effect of varying the moisture content 3 per cent above or below optimum moisture for maximum density results in different degrees of detrimental effects for different soils and their respective cement content, e.g., there exists a most favorable moisture content, which may or may not be equal for each different cement content used in a soil-cement mixture that will result in a minimum of cracking.

4. Early cracking that occurs in soil-cement mixtures can be attributed solely to the movement of the moisture in those mixtures. This movement is caused by evaporation and/or migration. Evaporation is the loss of water from the mixture to the atmosphere and is directly related to curing effectiveness. Migration is the movement of water in soils

possessing a high affinity for water and the movement of water to cooler regions. These movements are directly related to capillary attraction and temperature differential, respectively. It is recommended that

1. Any agency working with soil-cement develop and use a method similar to Test No. II, 70 deg. F. temperature differential during the early curing period, that will enable obtaining of the most desirable moisture content for minimum cracking for a predetermined specified soil-cement ratio. Also, from that method can be determined the maximim allowable deviation from the optimum that will not result in detrimental effects with respect to durability and cracking.

2. An extensive study to be made on numerous soils with varied clay and silt contents in order to provide a more concrete relationship between these silt and clay contents and cracking.

3. Research be performed on developing a curing compound that would decrease the existing temperature differential during the early curing period.

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